Atomic Energy Control Board
P.O. Box 1046
Ottawa, Canada
K1P 5S9

Commission de contrôle de l'énergie atomique
C.P. 1046
Ottawa, Canada
K1P 5S9

INFO-0096

REVIEW OF EXISTING INSTRUMENTATION AND EVALUATION OF POSSIBILITIES FOR RESEARCH AND DEVELOPMENT OF INSTRUMENTATION TO DETERMINE FUTURE LEVELS OF RADON AT A PROPOSED BUILDING SITE

by

DSMA Atcon Ltd.

A research report prepared for the
Atomic Energy Control Board
Ottawa, Canada

RESEARCH REPORT

January 18, 1983

FOREWORD

This report presents the results of a project carried out under DSS Contract 18SQ.87055-2-4039 on behalf of the Atomic Energy Control Board, Canada Mortgage and Housing Corporation, and the National Research Council. The work was carried out by DSMA ATCON LTD. with the collaboration of Acres Consulting Services Ltd..

TABLE OF CONTENTS

		Page No.
	SUMMARY/RÉSUMÉ	1
1.	INTRODUCTION	2
2.	PROBLEM REVIEW	2
2.1	Example Calculation	3
2.2	Problem Solutions	3
3.	SOIL AND SOIL AIR MOVEMENT	3
3.1	Geological History (G67, Fr79)	4
3.2	Physical Structure of the Soil (G67, Ma79)	5
3.3	Soil Water and Saturation	6
3.4	Permeability	6
3.4.1	Intrinsic Permeability	7
3.4.2	Apparent Air Permeability and Saturation	7
4.	SOIL AIR FLOW	7
4.1	Air Flow Resistance and Electrical Resistance	8
4.2	Calculation of Air Flow Resistance	9
4.3	House-to-Soil Pressure Differences	9
4.3.1	Stack Effect	10
4.3.2	Wind Forces	10
4.3.3	Total Pressure Differentials	10
4.4	Calculation of Soil Air Flow	11
4.5	Distribution of Air Flow	11
4.6	Radon Supply and Travel Time	12
5.	VARIATION OF SOIL PERMEABILITY	15
6.	SITE SELECTION PROCEDURES	15
6.1	Estimation of Permeability	15
6.2	Evaluation of Radon Release Rate from Soil	16
7.	MEASUREMENT OF PERMEABILITY	17
7.1	Permeameter Design	17
7.2	Permeameter Theory	18
7.3	Field Trials	18
7.4	Alternative Methods	

TABLE OF CONTENTS (Cont'd.)

		Page No.
8.	RADON RELEASE FROM SOIL	19
	8.1 General	19
	8.2 Gamma Ray Spectroscopy	20
	8.3 Choice of Detector System	21
	8.4 Evaluation of Detector Systems	22
	8.5 Field Trials	23
9.	SITE EVALUATION PROCEDURES	24
	9.1 Measurement Methods Summary	24
	9.2 Radon Index Number	24
	9.3 Site Evaluation Methods	25
10.	CONCLUSIONS	26
11.	ADDITIONAL WORK	26

REFERENCES

TABLE 1 - Porosity Values
TABLE 2 - Residual Saturation Values
TABLE 3 - Range of Permeability Values
TABLE 4 - Radon Escape Fraction and Soil Type
TABLE 5 - Calibration Constants

FIGURE 1 - Grain Size and Porosity
FIGURE 2 - Typical Variation of Air Permeability with Saturation
FIGURE 3 - Air and Current Flow
FIGURE 4 - Air Flow Resistance as a Function of Depth
FIGURE 5 - Distribution of Soil Air Flow
FIGURE 6 - Variation of Soil Moisture and Permeability with Depth
FIGURE 7 - Soil Permeameter
FIGURE 8 - Size Distribution and Texture
FIGURE 9 - Spectral Comparison of Environmental Radiation as Observed by a Germanium and a Sodium Iodide Detector

APPENDIX I - Reference List for Soil Permeability Measurement
APPENDIX II - Computer Modelling of the Movement of Radon Through Soil into Houses
APPENDIX III - Field Trip Report
APPENDIX IV - Environmental Gamma Spectroscopy Equipment

SUMMARY

The rate at which radon enters houses from the soil depends on:

- the pressure differential between the house and the soil;
- the resistance of the soil to gas movement; and
- the radon release rate of the soil near the house.

The pressure differential between house and soil is caused by wind forces and temperature differences, which depend on the size of the building and the season, and are therefore almost independent of the site location. The soil resistance (permeability) and radon release rate are site specific, and a computer study of radon movement through the soil suggested that these parameters could be combined to give a Radon Index Number (RIN) for a site that would be proportional to the radon entry rate into a typical house.

The methods available to measure soil permeability or radon release rate were reviewed, and laboratory methods were found to be fully adequate to provide the information required to calculate the RIN for a site. However, field methods suitable for rapid area surveys are available only for estimation of radon release rate (gamma ray spectroscopy). A number of soil parameters related to permeability such as texture or grain size distribution can be determined rapidly, but additional work is required to correlate them with permeability. If this work was carried out, then existing sources of information, and existing field and laboratory measurement techniques would enable estimates of RIN to be produced at regional, area, and site scales.

Regional RIN estimates would be produced using existing airborne gamma survey maps to estimate average soil radon release rate, plus agricultural soil classification maps to estimate permeability. Although these regional RIN estimates would be very approximate, they would identify those areas where more accurate estimates were required.

Area RIN estimates would be produced using portable gamma spectroscopy equipment to estimate soil radon release rates over an area, plus simple soil grain size analysis techniques to estimate permeability. These area RIN estimates would be approximate, but would identify those sites where more accurate estimates were required.

Site RIN estimates would be produced using laboratory techniques to measure both the radon release rate and the permeability of several undisturbed soil core samples taken at depths over the site. These would provide the most accurate value of RIN possible for a given site.

Development of new instruments is not required to predict the future levels of radon at proposed building sites. What is needed is a better understanding of the relationship between the soil parameters and the radon entry rate into a house. To do this, further theoretical work is required to find how the radon entry rate is affected by seasonal variations in soil permeability, porosity, and radon release rate. This can be done using three dimensional computer flow models. In addition, field work is required to actually measure the permeability and radon release rate of soil adjacent to houses where the radon entry rate is known to be high, so that the predictions of theory can be verified in practice.

DISCLAIMER

The Atomic Energy Control Board is not responsible for the accuracy of the statements made or opinions expressed in this publication and neither the Board nor the authors assume liability with respect to any damage or loss incurred as a result of the use made of the information contained in this publication.

R É S U M É

Le taux auquel le radon pénètre dans les maisons par le sol est dû à:

- la différence de pression entre la maison et le sol;
- la résistance du sol au déplacement des gaz; et
- le taux de libération du radon du sol près de la maison.

La force éolienne et les variations de température créent une différence de pression entre la maison et le sol suivant les dimensions de la maison et la saison, et presque indépendamment du site. La perméabilité du sol et le taux de libération du radon sont propres au site, et d'après une étude informatisée sur le déplacement du radon dans le sol, il semble que ces paramètres peuvent être combinés pour donner un numéro d'indice du radon (NIR) qui soit proportionnel au taux d'entrée du radon dans une maison type d'un site donné.

Les méthodes pour mesurer la perméabilité du sol ou le taux de libération de radon ont fait l'objet d'une révision et des méthodes de laboratoire se sont avérées efficaces pour produire l'information nécessaire au calcul des NIR d'un site. Cependant, les méthodes sur le terrain qui conviennent aux études rapides d'une région n'existent seulement que pour évaluer le taux de libération de radon (spectroscopie de rayons gamma). Quelques paramètres du sol reliés à la perméabilité comme la texture ou la distribution du grain peuvent être déterminés rapidement, mais il faut effectuer d'autres études pour établir leur corrélation avec la perméabilité. Si ce travail est fait, les sources d'information existantes et les techniques de mesure sur place ou en laboratoire existantes permettront d'évaluer les NIR à l'échelle de la région, du secteur et d'un site précis.

Les évaluations de NIR d'une région doivent être faites à l'aide de relevés cartographiques de rayons gamma en suspension dans l'air pour établir le taux moyen de libération du radon dans le sol, et à l'aide de cartes des sols d'agriculture pour en évaluer la perméabilité. Même si ces évaluations de NIR d'une région sont très sommaires, ils permettent d'identifier les secteurs où des évaluations plus précises sont nécessaires.

Les évaluations de NIR d'un secteur doivent être faites à l'aide d'un spectomètre à rayons gamma portatif pour évaluer le taux de libération du radon dans le sol d'un secteur, et à l'aide de techniques simples pour analyser le grain du sol et en déterminer la perméabilité. Les évaluations de NIR d'un secteur seraient approximatives, mais permettraient d'identifier les sites p écis où des évaluations plus précises sont nécessaires.

Les évaluations de NIR d'un site précis doivent être faites à l'aide de techniques de laboratoire pour mesurer le taux de libération du radon et la perméabilité des nombreuses carottes de sondage prises à différentes profondeurs dans le sol non remué du site. Ces évaluations pourraient fournir la valeur la plus précise possible des NIR d'un site précis.

Il n'est pas nécessaire de développer de nouveaux instruments pour prévoir le taux futur de radon sur l'emplacement de nouveaux édifices. Il importe plutôt de mieux comprendre la corrélation entre les paramètres du sol et le taux d'entrée du radon dans une maison. Pour y arriver, il faudra faire un peu plus de recherches théoriques pour trouver comment le taux d'entrée du radon peut être affecté par les variations saisonnières de perméabilité et de porosité du sol, et du taux de libération du radon. On peut utiliser un modèle d'ordinateur tridimensionnel pour faire ce travail. De plus, des recherches sur le terrain sont nécessaires pour mesurer la perméabilité réelle et le taux de libération réel du radon dans le sol adjacent aux maisons où l'on sait que le taux d'entrée du radon est élevé, afin que les prévisions théoriques puissent être vérifiées en pratique.

1. INTRODUCTION

There are several areas in Canada where the average radon concentration in existing houses is significantly higher than the general average of 1-2 pCi/litre. Investigation programs carried out in uranium mining areas (Bancroft and Elliot Lake, Ontario and Uranium City, Saskatchewan) found the cause of these elevated levels was that radon generated in the ground was carried into these houses by a mass flow of soil gas, and that the concentrations could be reduced by closing the joints and openings in the foundations connecting to the soil, or by reducing the pressure differentials between the house and the soil (A78, A79, A80). Methods for implementing both these approaches in new housing have been developed, and approved by CMHC (A79), but although the cost is only a fraction of the cost of retrofitting, it is still high enough that it is undesirable to require 'radon resistant' houses in areas where they are not needed. Conversely, it is undesirable to expose families to high levels of radon if it could be avoided. The crucial question for planning authorities is therefore 'How do we tell if radon resistant construction is required at a particular building site?'

At present, a partial answer to this question is available only in those few communities where a radon-in-housing survey has been carried out. At some of these locations all radon concentrations were low, and so the answer there is clearly 'no'. In most of the communities surveyed, however, high radon concentrations were found in some houses and so the answer here is 'perhaps'. Interestingly, even in the communities where many houses had elevated radon concentrations, the concentrations in most of the houses were still close to the normal value of 1-2 pCi/litre. This suggests that the soil conditions needed to produce elevated radon concentrations in houses may be localized in relatively small areas. If those areas could be identified, then there would be a justifiable basis for requiring radon resistant foundations in such locations, or diversion of development to other areas. The development of instrumentation and measurement procedures to rapidly identify radon prone areas would greatly assist planning authorities in areas that may have elevated radon levels in houses.

2. PROBLEM REVIEW

Elevated radon concentrations in houses are caused by the entry of soil gas containing radon generated in the soil. The pressure differentials that draw soil gas into the house are produced by wind forces and the temperature differences between the house and the exterior (stack effect), and the overall sum of these is such that the pressure in the building interior is less than that in soil adjacent to the foundations. The rate at which soil gas enters the house depends on the

- pressure differential between house and soil,
- resistance of the foundations to gas flow,
- resistance of the soil itself to gas movement.

The radon concentration in a building depends on

- radon supply (soil gas flow x radon concentration),
- building volume,
- ventilation rate.

2.1 Example Calculation

A typical house has a volume of about 400 m^3, and when occupied, has about 0.3 air changes per hour. The AECB criterion for remedial work in houses in uranium mining areas (A77) is equivalent to an average radon concentration of 5-7 pCi/L, and concentrations exceeding 10 pCi/L have been observed in many of those houses. To average 10 pCi/L in such a typical house requires a radon supply rate of 1.2×10^6 pCi/hour. Radon concentrations in soil gas entering the house were often of order 1000 pCi/L, and so a soil gas entry rate of 1.2 m^3/h would provide that supply rate. An opening only 2 cm^2 in area would allow this flow rate under the typical house-to-soil pressure differential of 5-10 Pa. Joints and openings in poured concrete basements usually total 300 cm^2 or more, so it is clear that the major resistance to the movement of soil gas into a house is not the building fabric, but rather the resistance of the soil to gas movement.

Radon in soil gas is produced by radioactive decay of radium in the soil, and 132 pCi of radium produces 1 pCi/h of radon. Soils contain about 1.0 pCi/g, but much of that radium is in the interior of the mineral crystals that make up the individual soil particles, and so only about 30-40% of the radon produced can escape. Approximately 380 g of soil are therefore required to release 1 pCi/h to soil gas, and accordingly,

a radon supply rate of 1.2×10^6 pCi/h to a house is equivalent to the radon release rate from 4.5×10^8 g of soil. The bulk density of soil is about 1.5 g/cm^3, so this mass of soil would occupy 300 m^3.

A typical house has 140 m^2 of basement floor and walls in contact with the soil, and so 300 m^3 is equal to the volume of a layer of soil 2 m thick adjacent to the basement. It is unlikely that 100% of the radon released in this layer will enter the house, but clearly, even in soils of average radium content, there is enough radium within a few metres of the basement walls to support elevated radon levels in the house.

2.2 Problem Solutions

The problem of predicting the radon level in a house to be built at a particular site is essentially the problem of predicting the radon supply rate into the house. As a major component of this problem is predicting the flow rate of soil gas into a house, an understanding of the influence of soil type on air movement is required. A brief review is given below.

3. SOIL AND SOIL AIR MOVEMENT

3.1 Geological History (G67, Fr79)

Canada was almost entirely covered by Pliestocene glaciers, and the unconsolidated surficial materials (soil) that cover the bedrock are predominantly of glacial origin. They are composed mainly of fragments from the local rock, though there may be appreciable amounts of material that have been transported many miles. Some materials were deposited directly from the ice, others were deposited from running or standing melt-water, and as the deposition processes varied from place to place the deposits are heterogeneous.

The materials of greatest areal extent are glacial till and glacial lake clays and silts. Till is composed of a mixture of all sizes of material, and in the Precambrian Shield areas, is generally sandy with some silt and little clay. In areas of sedimentary rock, the till often has considerable silt and clay. Many tills contain large pebbles and cobbles in their lower layers. The thickness of these deposits is usually

tens of metres, but they can be more than a hundred metres thick.

Lake clays and silt were deposited in lakes dammed by ice, and their extent and thickness depends on the size of the lake, the supply of material and the length of time the lake existed. Thicknesses can range from a few centimetres to more than 30 metres. As they were deposited by settling in water, the upper surfaces tend to be flat.

The melt-water from the glaciers carried away materials and sorted them. The larger fragments were deposited close to their origin as sands and gravel, while the finer silts and clays were carried away and deposited in distant lake basins or estuaries. The shape, extent and thickness of these deposits depends on the underlying topography.

In addition to these melt-water deposits, many areas of Canada have deposits of sand and gravel that were formed on top of masses of stagnant ice during periods of glacial retreat. When the underlying ice finally melted, these 'collapsed outwash' materials were deposited on the surface, producing gravel ridges, or partially filling eroded valleys.

Finally, some areas, particularly the Great Plains, have surface deposits of wind-borne fine sands or silts. The most common deposit is a fine silt called loess. After the glaciers melted, the present drainage system developed and all these materials were eroded and reworked by the processes that are still in action today.

3.2 Physical Structure of the Soil (G67, Ma79)

Underlying all soils is bedrock, which is covered by the fine fragments of rock discussed above. These fragments are separated from each other by pore spaces through which air and water may move. This layer is called the regolith. At the top of the regolith is a zone where the structure and chemistry has been modified by the presence of plant roots, leaching, and biologic activity. This is called the solum. The thickness varies from area to area, but is generally less than 30 cm. Finally, there is a layer of organic matter a few cm thick (humus) covering the soil.

As the procedures of site development normally remove the humus and much of the solum, it is the regolith that comprises the soil in or on

which the house is built. We can therefore discuss the properties of 'soil' in terms of the properties of the regolith.

The mineral fragments that make up the regolith are irregular in shape and vary widely in size. The size range of the particles that make up certain characteristic deposits is shown in Table 1. Most of the larger particles are comprised of Quartz (SiO_2) because of its resistance to weathering and its abundance in granitic rocks. The smaller particles have been produced by weathering of less resistant minerals to aluminum or magnesium silicates (clays). These silicates are not inert like quartz, and can react with soil water and the cations dissolved in it. The physical properties of soil containing large amounts of clays depend greatly on the amount of water in the soil.

As soil particles are irregular in size, spaces between them (pores) are also irregular in size and shape. The fraction of the soil volume that is composed of pores is called the porosity. Table 1 shows porosity and grain size values for selected types of deposit. The distribution of particle size in a deposit influences porosity, for small particles are more difficult to pack tightly than large, but small particles can also fit between the gaps of large particles to give denser mixtures.

3.3 Soil Water and Saturation

All natural soils contain water, and the fraction of the pore volume that is filled with water is called the saturation. The force of gravity acting on soil water tends to drain water from the soil, but this is resisted by capillary forces developed in the narrow channels between the grains. As a result, soils tend to drain to a constant saturation, equal to the fractional volume of soil pores too small to drain under gravity. This is termed the 'field capacity' or residual saturation, Sr. It is approximately the fraction of the pore volume that is included in pores of less than 15 micrometres effective radius. Table 2 gives values of Sr for three selected types of deposit. The high value of Sr for clays is due partly to their small particle and hence pore sizes, and partly to the fact that clays tend to swell when they are wetted, thereby closing the smaller intergranular passages and trapping water.

3.4 Permeability

3.4.1 Intrinsic Permeability

The flow of a liquid or gas that fills all the pores of a medium has been studied extensively, and can be described by Darcy's equation.

$$V = \frac{k}{\mu} \cdot \frac{dP}{dx} \qquad (1)$$

where: V = flow velocity in the x-direction,
dP/dx = the pressure gradient,
μ = fluid viscosity, and
k = the permeability.

As the flow through a capillary tube or a soil pore is proportional to its cross-sectional area, the permeability of a soil is proportional to the cross-sectional area of the pores. As pore diameters are related to the soil grain diameters, the permeability for many soils can be estimated approximately as:

$$k = 10^{-5} (d_{10})^2 \ cm^2 \qquad (2)$$

where d_{10} is the soil grain diameter (mm) at which 10% of the mass of the soil particles are finer(Fr79). This can be determined easily by sieve analysis on dried soil.

If the soils contain clays, this equation overpredicts permeability since the small clay particles block the larger pores through which most of the flow passes. In all cases, the permeability depends mainly on the size of the larger pores and their fraction of the total pore volume. Figure 1 illustrates the relation between particle size distribution, pore size distribution, and porosity for a silty clay (Ge79). The permeability of this soil depends almost entirely on the fraction of the porosity associated with the pores of more than 3 micrometres diameter. As the distribution of soil pore sizes is fixed for a given sample, the value of k is also fixed. Table 3 shows the variation of permeability with soil type.

3.4.2 Apparent Air Permeability and Saturation

The permeability of a porous medium measured by a gas is always larger than the permeability measured by a liquid, even if the liquid does not react with clays. The difference ranges from a few percent in the case of coarse sands, but may be a factor of 2 or 3 in the case of silts and clays. The reason for this is that the mean free path of gas molecules is comparable to the diameter of the smaller soil pores, and under these circumstances, the gas velocity at the walls of the pore is not zero.

When a soil sample is wetted, some of the pores become filled with water which prevents the passage of air. The apparent air permeability will decrease, and if enough water is added, will fall to zero. Figure 2 shows the variation of apparent air permeability with saturation (Co77). Increasing saturation initially has little effect on the air permeability until Sr is reached, where upon the permeability falls rapidly, reaching zero at about 80% saturation. At low saturations, the water is present predominantly in the smallest pores. Closing them to the passage of air makes very little difference to the total air flow, as most of the air passes through the larger pores. It is not until the saturation reaches Sr that water starts to fill the larger pores, reducing the air flow.

As the average moisture content of field soils remote from the water table is close to Sr, except when it is raining or for a short period thereafter, the average air permeability of field soils can be expected to be close to the intrinsic permeability, and so the k values given in Table 3 are reasonable estimates of the average apparent air permeability of those soil types.

4. SOIL AIR FLOW

4.1 Air Flow Resistance and Electrical Resistance

The flow rate Q of a fluid with viscosity μ through a prism of soil with effective permeability k, cross-section A, length L under a pressure difference P is given by Darcy's Law.

$$Q = \frac{k}{\mu}.\frac{P}{L}.A \qquad (3)$$

The flow of current I through a prism of a conductor with resistivity ρ, cross-section A, length L under a voltage difference V is given by Ohm's Law.

$$I = \frac{1}{\rho} \cdot \frac{V}{L} \cdot A \qquad (4)$$

As both Darcy's Law and Ohm's Law are similar in form, we can use the flow of electricity in conducting media as an analog of the flow of air in soil, and thereby use the tabulated values of electrical resistance to estimate the air flow resistance of the soil.

4.2 Calculation of Air Flow Resistance

Houses constructed with concrete basements have the floor poured inside the walls, and so there is a small shrinkage gap (about 1 mm) around the periphery of the basement floor. When the pressure in the house is lower than outside, air flows through this gap from the soil to the house. A corresponding volume of air must enter the soil surface at some place outside. The flow rate of soil air into the house is therefore determined by the pressure differential between the house and the soil surface and the air flow resistance of the soil that lies between the crack and the soil surface.

Figure 3A shows the flow of air into a crack in the basement through the soil, and 3B shows the flow of current between an infinite surface electrode and a horizontal conductor. The similarity is obvious. For a conductor of length L, radius r, buried at a depth X in a medium of resistivity ρ, the resistance is (La77):

$$R = \frac{\rho}{2\pi L} \cdot \text{Cosh}^{-1} \frac{X}{r} \text{ ohms} \qquad (5)$$

The resistance of the soil to gas movement from surface to a horizontal crack in a basement wall of length L, width 2a, at a depth D, is therefore:

$$F \propto (2) \frac{\mu}{k} \cdot \frac{1}{2\pi L} \cdot \text{Cosh}^{-1} \frac{D}{a} \qquad (6)$$

(The factor of 2 arises as the crack is in a wall, so only half the soil is available to conduct air compared with the electrical case.)

Figure 4 shows the variation of F with depth for two different crack widths. Note that F is not very sensitive to crack width, and that once the depth exceeds 50 cm, F increases very slowly with depth. This shows F is determined mainly by the effective permeability of the soil within 50 cm of the crack. Accordingly, we can take the resistance of a horizontal crack in a basement wall to be approximately constant, regardless of depth. Assuming that cracks are no more than 1 mm wide and at least 1 m below the surface, then $\text{Cosh}^{-1}\ D/a \geq 8.3$.

Accordingly, by substitution of $\mu = 1.8 \times 10^{-4}$ poise, and evaluation,

$$F = \frac{4.8 \times 10^{-4}}{L.k} \qquad (7)$$

The flow rate of soil air into a typical house is $Q = \frac{P}{F}$ cm^3/s, or

$$Q = \frac{L.k.P}{4.8 \times 10^{-4}} \text{ cm}^3/\text{s} \qquad (8)$$

where: L = total crack length (cm)
k = apparent permeability (cm^2)
P = pressure differential (dynes/cm^2)

4.3 House-to-Soil Pressure Differences

The major sources of house to soil pressure differences are temperature differences (stack effect) and wind forces.

4.3.1 Stack Effect

The air in a house is usually warmer than that outside, and therefore less dense. The air column in a house is approximately 5 to 7 m tall and a difference in temperature of 1°C between outside and inside will therefore produce a total pressure unbalance of 0.2 Pa. Winter temperature differences are in the range of 20-50°C, so the stack effect produces unbalanced forces of 4-10 Pa. Air leakage into the house usually results in a neutral plane at the first floor level, so the suction at the basement floor level is often less than half of this or 2 to 5 Pa. In

the summer the minimum pressure differential is set by the difference between soil air temperature and basement air temperature, about 1 Pa, but wind forces are generally more important then.

4.3.2 Wind Forces

The pressure exerted on a wall at right angles to an air flow with speed V km/h is $P = 0.048\ V^2$ (Pa). Similar pressure is exerted on the ground in front of the wall, and a comparable suction pressure is exerted on the downwind side of a building. For an average wind of 10 km/h, the maximum pressure on the upwind side of a house will be about 5 Pa higher than atmospheric, and the minimum pressure on the downwind side will be about 5 Pa lower than atmospheric. As the low pressure zone covers a larger area of the house than the high pressure zone, air tends to leak out of the house and thus lower the house pressure to 1 or 2 Pa less than atmospheric. The pressure differential between the upwind soil surface and the house interior therefore can be as high as 7 Pa.

The pressure depends on the square of the wind speed, and the pressure distribution over a house depends greatly on wind direction, both of which vary continually. As a result, we can expect not only the pressure differential to vary continually, but also the area of soil exposed to higher pressures to be constantly changing.

4.3.3 Total Pressure Differentials

The total pressure difference between the basement floor of a house and the exterior soil surface is equal to the sum of thermal and dynamic forces, and typical values range from as high as 17 Pa for an upwind area in winter, to -2 Pa for a downwind area in summer. Average values would be about 10 Pa for the upwind walls, and 0 Pa for the downwind walls.

4.4 Calculation of Soil Air Flow

Elevated house radon concentrations in the uranium mining districts were associated with soil air flows in excess of 1 m^3/h into a house. Using the parameters given above, we can estimate the apparent air permeability needed to allow such flows. Assuming that air flows into

the basement via the upwind portion of a single wall-floor joint crack, which has an effective length of 17 m, and the average pressure difference is 10 Pa (100 dynes/cm^2), then the value of k that will allow a flow rate of 1 m^3/h (278 cm^3/s), is given by substitution in equation (8).

$$k_c = \frac{4.8 \times 10^{-4} \times 278}{1700 \times 100} = 8 \times 10^{-7} \text{ cm}^2 \qquad (9)$$

The calculation is only an approximation to a much more complicated reality, so too much weight should not be given to the value of k_c obtained above, but it does suggest that soils with in-situ permeability comparable to that of sands can allow sufficient soil air flow to produce elevated radon concentrations.

4.5 Distribution of Air Flow

The distribution of current flow from a surface electrode to a buried conductor is known(La77), and the steady state distribution of air flow through the soil surface to a basement crack is similar. At a point distance X from a wall with a crack at depth d, the air flow per unit area is proportional to $(X^2 + d^2)^{-1/2}$. Integration of this expression gives the amount of air entering the soil as a function of distance, as shown in Fig. 5. Equal amounts of air flow to the basement between the flow lines shown, and 75% of the air reaching a crack at depth d enters the house within a distance of 2.4 d from the wall. Figure 5 also shows that the flow distribution to a wall/floor joint crack can be approximated by the flow distribution to a virtual crack of similar dimensions but located at about 1.5 m greater depth.

4.6 Radon Supply and Travel Time

Radon released from the soil is carried to the house along the flow lines, but some of the radon will undergo radioactive decay before it reaches the house. As the half life of radon is 92 hours, virtually all of the radon released more than 300 hours travel time away from the house has decayed before reaching the house. In effect, the volume of soil from which radon can be collected lies within 300 hours travel time.

An analytical expression for the travel time along a flow line is not available, so a 2-dimensional numerical computer model of the soil and basement was used to compute the soil air flows produced in the soil and through basement openings by the surface pressure distributions around a basement, and the corresponding radon concentrations. Appendix 2 describes the model, the calculation procedure, and presents the results in full.

The higher pressures upwind of a house cause air to flow into the soil, and to reduce the radon concentration outside the basement walls and beneath the floor. As the wind is never constant in speed or direction, air is continually being forced into different areas of the soil, and so the radon concentration at a point depends greatly on the history of the wind speed and direction over the previous 24 hours.

The model indicates that the total radon supply rate into a basement varies as $k^{0.7}$ for although higher permeabilities allow higher soil gas flows, they also allow air to enter the soil more readily and dilute the radon concentration. As the model is much simpler than reality, the value of these calculations is not that they show conclusively that the size of the collection zone varies as $k^{0.70}$, but that they suggest that the radon supply rate into a house varies less rapidly than permeability. Even poor estimates of permeability may be sufficient to distinguish between sites with potentially high or potentially low radon supply rates.

5. VARIATION OF SOIL PERMEABILITY

The above theoretical calculations are based on the ideal case of a uniformly porous medium. We know, however, that the apparent permeability of soil is not uniform, and this gives rise to two separate problems, - what is the effect of variations in permeability on the radon supply, and how do we evaluate the effective permeability?

In many areas of Canada the soils are gravels and sands deposited by water, and as the velocity changed with time, the size of the grains deposited also changed, causing horizontal layering in these deposits.

As air flows more readily through coarse grained deposits than fine, the horizontal permeability (along the coarse layers) is much higher than the vertical permeability (through the fine layers). The effect of this anisotropy on radon supply is shown to be small in Appendix 2.

Most soils are uniform in type with depth, so that the near surface permeability is representative of the permeability of the deposit as a whole, but there is always the possibility that the permeability can change greatly with depth. Accurate estimates of soil permeability therefore require samples to be taken down to below the footing levels. Near-surface measurements are valuable for screening tests, but can be misleading.

In addition to the variations in permeability caused by variation in the soil structure, the presence of soil water introduces a variation even in uniform soils. The fraction of the pore volume that is filled with water (saturation) increases from a low value near the surface to nearly 1.0 at the water table. As discussed in section 3.4.2, the apparent permeability of soil therefore varies from a value near the intrinsic permeability at the surface to a value of zero close to the water table.

Figure 6 shows typical variation of saturation with depth for two extreme soils, and the calculated variation of relative permeability with depth for each soil. The soil water content is close to saturation for a distance above the water table that depends on the size of the soil pores. For sands this capillary fringe is less than 50 cm thick, whereas for clays it can be 2 m or more. Above this zone, the saturation approaches the residual saturation Sr, and permeability is virtually constant until the surface is approached. The reduction in saturation in the upper few cm hardly affects the permeability, for water is removed from the smaller soil pores, which do not contribute greatly to air flow.

Most areas selected for building have water tables at some depth below the footing level, and drainage is provided around basements at footing level, so we can expect that the moisture content of the soil close to the basement will be close to Sr. As a result, the apparent permeability of the soil close to the basement will be relatively unaffected by precipitation and moderate fluctuations in water table depth.

Short term variations in water content occur in soils following rainfall or snow-melt, and high values of saturation occur near the surface as precipitation drains down through the soil. Even in sands, it can take several days before the wetting front has moved through the soil to the water table and the moisture distribution has returned to near its equilibrium case. The effect of saturation variations on the near surface permeability measured in-situ can be reduced but not eliminated by delaying measurements for a day or so after precipitation to allow the upper layer of the soil to drain back to near the residual saturation. Samples for laboratory analysis can be allowed to drain to residual saturation before permeability is measured, and so are not affected by saturation variations.

Despite the problems associated with near surface measurements of any type, they may well be valuable for screening purposes. Taking samples at depths of more than 1 metre requires elaborate equipment, and it would be desirable to detect problem areas before large sums of money were spent on sampling. For example, at Elliot Lake the soil was a glacial deposit with layered sands, gravels and cobbles. It was difficult to drive a small tube suitable for in-situ porosity measurement to depths of more than 30 to 60 cm before refusal on a small stone, and even powered 3 inch augers could not penetrate more than 100 - 150 cm before refusal. A large 6 inch diameter hollow-core auger powered by a tractor-mounted hydraulic motor was able to penetrate to depths of 2-3 m but even that was frequently stopped by striking 10 cm diameter cobbles at depth.

Large areas of Canada are covered with similar deposits, and equipment of this size, weight, and power is required to obtain undisturbed soil samples to greater than basement depth. This equipment is clearly too elaborate to be desirable for early investigation, so simpler screening methods are required.

6. SITE SELECTION PROCEDURES

As shown in the preceeding section, the radon supply rate into a house is a function of the release rate of radon from the soil and a fractional power of soil permeability. A site index number can therefore be calculated from their product, and below some critical value of that index, conventional housing will have radon supply rates too low to cause indoor radon concentrations in excess of some standard. The critical index value will vary with the standard, and housing type, for the lower ventilation rates in modern housing will lead to higher concentrations for the same radon supply rate. The actual size of the critical index may have to be determined by a mixture of calculation and field experiments, but in principle, once the critical value has been established a site can be selected or rejected on the basis of only 2 parameters - soil apparent permeability and radon release rate.

6.1 Estimation of Permeability

As soil permeability is a function of grain size distribution, and hence soil type, a crude estimate of permeability can be made simply on the basis of soil type, i.e. sand, silt, clay, etc. This information is summarized for many areas on agricultural soil maps. Table 3 shows that even such crude descriptions such as 'silt' enable the permeability of the soil to be estimated to within 3 orders of magnitude, and so soil maps alone may be sufficient to classify areas as suitable, unsuitable, and requiring more detailed investigation. The first stage of that investigation could be simply standard particle size analysis of soil samples, from which the permeability can be estimated. If further investigation is still needed, the apparent air permeability of the soil can be measured either 'in-situ' or in the laboratory on 'undisturbed' soil samples. These procedures are discussed further in section 7.

6.2 Evaluation of Radon Release Rate from Soil

The radium in soil undergoes radioactive decay and produces the gas radon. Only a fraction of the radon atoms produced in a soil grain can escape to the pore space before they, in turn, decay to a stable metal atom. The radon release rate of the soil therefore depends on the

concentration of radium in the soil and the escape fraction. Although both these parameters do vary, radium is so common an element in the earth's crust that concentrations vary by less than a factor of 5 over much of the regolith. The geochemical history of most soils is sufficiently similar that the radon escape fractions do not vary greatly from soil type to soil type. The average soil radium concentration is known over many km^2 of Canada as the result of aerial surveys intended for uranium exploration, so many areas can be rapidly classified from these surveys. If the site is too small to be properly evaluated from aerial surveys, or not included in them, the soil radium or the soil radon release rate can be estimated from in-situ measurements or from laboratory tests on soil samples. These procedures are discussed further in section 8.

7. MEASUREMENT OF PERMEABILITY

A literature survey was carried out of methods used to measure the apparent air permeability of soil, and the references are listed in Appendix 1. The basic laboratory method is to apply a steady air pressure gradient to a soil core and measure the air flow rate through the sample. Permeability is then given directly by Darcy's Law. The major problems are those of ensuring that the core is not damaged by handling, maintaining the water content, and of obtaining a representative sample. As most of the air flow through a soil core is via the larger pores, the compaction produced by taking the core sample can reduce the permeability. Very few laboratories are equipped for these measurements.

These problems have encouraged the development of in-situ measurement methods based on the injection of air into the soil at constant pressure and measuring the resulting flow, which is directly related to the permeability. The instruments were developed by agricultural researchers, who were interested only in the permeability of the solum - the zone of plant growth, and so their equipment was designed to measure high permeabilities at depths of less than 10 cm. None of the equipment described is commercially available. Accordingly, an in-situ permeameter based on these designs was constructed to measure at depths of 50-60 cm, to test the utility of the concept.

7.1 Permeameter Design

Figure 7 shows a sketch of the permeameter, which consists of three parts: a soil probe; pressure and flow measurement devices; and a compressed air cylinder. To use, a soil sample tube is placed over a sharpened mandrel, and the two driven into the ground together by hammer blows on the mandrel head. The exterior of the sample tube is smeared with petroleum jelly to provide lubrication and to seal the tube into the ground. When the desired depth is reached, the mandrel is removed, and an air hose attached to the top of the sample tube. Air from the air cylinder is let into the sample tube, at a rate controlled by a pressure regulator, and the pressure and flow rate are read on the manometer and the rotameter.

7.2 Permeameter Theory

The electrical resistance between a spherical electrode radius r, buried at depth D, in a conductor with resistivity ρ, and a surface electrode is:

$$R = \frac{\rho}{4\pi}\left(1 + \frac{r}{2D}\right) \qquad (10)$$

so, by analogy with Darcy's Law, the flow rate, Q, from such a cavity to the soil surface under a pressure, P, is:

$$Q = \frac{4\pi k}{\mu} \cdot \frac{P}{(1 + r/2D)} \qquad (11)$$

or for $D \gg r$,

$$k = \frac{Q\mu}{4\pi P} \ cm^2 \qquad (12)$$

or in field units,

$$k = 2.5 \times 10^{-7} \ Q/P \qquad (13)$$

where: Q = litres/min
P = cm of water

The value of k obtained is averaged over a soil volume of approximately $2D^3$.

Air can be treated as an incompressible fluid up to a pressure of about 60 cm H_2O, so the Darcy equation can be used without modification up to that pressure. Above that pressure, the permeability starts to be under-estimated. The air flow must be corrected to standard conditions, and the indicated flow rate on the rotameter corrected for density effects.

7.3 Field Trials

The equipment used measured air flows up to 0.5 litre/min, and pressures up to 60 cm H_2O. The highest value of k measurable was 1×10^{-7} cm^2 and the lowest value was 2×10^{-10} cm^2. As problem areas were expected to have apparent permeabilities of order 10^{-7} cm^2, this was believed to provide an appropriate range. Measurements were made on a range of soil types. Results are reported in Appendix 3. In general, the device worked well, but it was difficult to insert the probe in rocky or stoney soils, and highly saturated surface soils gave misleadingly low readings. As a result, a field permeameter does not appear to be a complete solution to the problem of estimating the average soil permeability at a building site.

7.4 Alternative Methods

The permeability of a soil is closely related to the amount of clay present, which is related to the 'texture' of the soil. A soil classification system is available to identify soils on the basis of their average particle size and the fraction of mass that is clay, and so it is possible that in-situ air permeability might be more closely related to the texture classes defined by this system. Figure 8 shows examples of 3 soils of different permeabilities classified by this method.

Most building sites are not situated in completely virgin country, so it is often possible to obtain soil samples both from the surface and at depth from the activities of other agencies. If the relationship between permeability and texture class were well established, the range of radon index number for a site could rapidly be calculated from simple sieve analysis of a few soil samples.

8. RADON RELEASE FROM SOIL

8.1 General

The radon release rate from a soil sample can be measured directly by sealing a known soil volume into a container and measuring the radon concentration in the container after 30 days have elapsed. At this time the radon release rate of the soil is equal to the decay rate of the radon in the volume, and can be calculated. Although the method is simple and accurate, the 30 day delay needed for radon to come to equilibrium with radium makes it unacceptable as a rapid survey technique.

A more rapid method takes advantage of the fact that decaying radon and radium atoms release penetrating gamma rays (photons) which can leave the soil so the radioactivity can be measured remotely. A measurement of the rate at which gamma rays leave the soil provides an estimate of the total amount of radon and radium in the sample, and the radon release rate can be calculated if the escape fraction is known.

The radon escape fraction, E, has been measured for a variety of soils, as shown in Table 4. The measurements are made on oven dried soil, and are therefore minimum estimates. The escape fraction of moist soils is nearly double that of oven dried soils (St82), due in part to the effect of surface water layers on the grains stopping those recoiling radon atoms that would otherwise have sufficient energy to cross an air-filled pore and bury themselves beyond escape in the surface of another grain. Table 4 shows that most values of E for dry soil are 15 to 20%, and so we can take E for moist soils as virtually constant at 0.35. Gamma ray measurements are therefore well suited to quick estimates of radon release rate.

Unfortunately the parent element of both radium and radon is not the only radioactive element present in the soil, for both thorium and potassium are radioactive, and have similar gamma ray activities in many soils. Discrimination between photons from the uranium decay chain and those from thorium and potassium decay chains is therefore required, and is performed by gamma ray spectroscopy.

8.2 Gamma Ray Spectroscopy

The higher energy gamma rays released by the decay of radon and radium are energetic enough to penetrate 10 to 20 cm of soil and so a detector suspended a metre above a field 'sees' a fraction of the photons emitted from an area about 4 m in radius and at least 10 cm thick - equivalent to a sample of about 8 tonnes of soil. This is a much larger mass than the 1 kg usually taken for laboratory analysis, and is much more representative of the soil as a whole. The large 'sample' mass also gives a higher sensitivity, so that the soil radionuclide content can be estimated with only a few minutes counting time.

Gamma ray spectroscopy can be carried out by either sodium iodide (NaI) scintillation detectors, or solid state diode detectors, usually made of germanium (Ge).

The NaI detectors produce a light flash when struck by a photon, and the light is detected and converted into an electrical pulse by a photomultiplier tube. The number of steps involved mean that the photomultiplier pulses from photons of the same energy are not identical, but vary about ± 6% from the average value (low resolution). These detectors are available readily in sizes of up to 1500 cm^3 (high efficiency) and they operate at ambient temperature.

The germanium detectors operate at cryogenic temperatures where they are able to collect essentially all the electons released within the detector when struck by a photon. This process is so direct that the electrical pulses from photons of the same energy vary less than 0.1% (high resolution). They are available in sizes up to 150 cm^3, but 50 cm^3 is more common (low efficiency).

The price per cm^3 of Ge detector is much higher than the price of NaI, and the price differential between systems is increased still further by the more elaborate equipment required to utilize the much greater amount of information presented in the Ge spectrum. In many cases this increased information content gives performance so much superior to that of the NaI system the additional costs can be justified.

Figure 9 shows the pulse height spectrum produced by the natural environmental radionuclides in both a 'large' Ge detector of about

35 cm^3 effective volume, and a 'small' NaI detector of 125 cm^3 volume. The difference in resolution between the detectors is very obvious, the Ge spectrum showing 25 clearly resolved lines, whereas the NaI spectrum shows only three broad peaks, at 1.46, 1.76, and 2.62 MeV. These are characteristic of K-40 (potassium), the most intense gamma rays of Bi-214 (a decay product of radium), and TL-208 (a decay product of thorium).

8.3 Choice of Detector System

If our purpose was to detect the presence of man-made radionuclides, such as fall-out, the choice would be clear cut. Only the Ge system has sufficient resolution to allow the unambiguous separation of man-made radionuclides from the natural ones (e.g. Zn-65 from Bi-214). However, as we wish only to estimate rapidly the radium content of the soil, the choice is less clear cut. Radium has a weak (5.5%) gamma ray of 0.186 MeV, and so soil radium concentrations can be measured directly using that ray. Unfortunately, the low energy limits the depth of soil that the gamma ray can penetrate, and the effective sample volume and sensitivity is reduced compared with gamma rays of more than 1 MeV. This, coupled with the low intensity, plus the high background of scattered gamma rays in the 0.2 MeV range, means that this peak is only visible in a Ge spectrum, and even then long counting times are required to estimate radium concentrations to $\pm$ 20%.

On the other hand, the decay of radium ultimately produces Bi-214, which has a number of intense, high energy gamma rays, so its concentration in the soil can be measured relatively rapidly, and the radium concentration inferred. As the 1.76 MeV Bi-214 gamma ray is easily resolved by NaI, we can use either NaI or Ge detectors if this route is followed.

Radium concentrations can only be inferred from Bi-214 measurements, because radium does not decay directly to Bi-214, but to radon, which is a gas. As the half life of radon is nearly 4 days, a radon atom has plenty of time to travel some distance from where it was born, and so the distribution of radon in the soil can be quite different from that of its parent radium. When the radon atom decays, it produces Po-218, a metal atom which attaches itself rapidly to any nearby surface, where

it decays to Bi-214. The distribution of Bi-214 is therefore controlled by the distribution of radon in the soil, not the distribution of radium. Fortunately, most of the radon is trapped within soil grains or soil water close to the radium that produced it with only a fraction actually mobile in the soil gas. We can therefore put limits to the variation of the ratio of Bi-214 to Ra-226.

In the upper layers of the soil there is a continual loss of radon from the soil gas to the atmosphere, the result of exchange and mixing processes. As a result, the concentration of Bi-214 in the upper soil is less than the concentration of Ra-226. Only 35% of the radon produced in a soil grain escapes to the soil gas, so even if all of this is lost to the atmosphere, the near surface Bi-214 concentration would be about 65% of the Ra-226. We would expect this to be a minimum, for surface vegetation reduces the loss-rate, so that generally the Bi-214 concentration can be expected to be 80% of the Ra-226, with an uncertainty of no greater than ± 20%. As this uncertainty is comparable to that of counting the Ra-226 gamma emission directly, the choice between the methods can be made mainly on grounds of convenience and cost.

8.4 Evaluation of Detector Systems

For many years the only group interested in radioactivity measurements in the field was the uranium prospecting industry. Their pressing requirements are sensitivity and portability, and they have been met by production of robust, portable four channel spectrometers plus NaI detectors. These are used to estimate uranium content from Bi-214 content, and to distinguish between radioactivity due to uranium and that due to potassium and thorium.

Recent events in the nuclear power industry have created another group interested in measuring low levels of man-made radionuclides in the field, and distinguishing them from the natural radionuclides. Their requirements are selectivity and portability, and they have been met by production of portable multi-channel analyzers plus portable Ge detectors in small dewars.

Manufacturers of both types of instrument were contacted, and data

specification sheets, equipment descriptions, and approximate prices are included in Appendix 4. In general, the cost of a Ge detector based system was about $25,000, whereas the cost of NaI detector based system was about $10,000. In addition, the sensitivity of the largest Ge was no more than 30% of a moderately sized NaI detector.

The photo-multiplier tube used with NaI detectors varies in electrical gain with temperature, as does the rest of the electronics. A pulse height change of 1% can be caused by a temperature change of $2^{o}C$, and as temperature changes of $10^{o}C$ over a day are common, the pulse height spectrum can shift significantly during the day. Temperature produced gain shifts in the detector are not a problem with Ge detectors, for they are maintained at 77K by boiling off liquid nitrogen from their insulated container.

The simplest solution to the gain shift is frequent recalibration - which is inconvenient and time consuming. A superior method is essentially continuous calibration, where a small source is incorporated in the detector, and the gain of the amplifier is electronically varied to keep the gamma peak from that nuclide at a fixed pulse height, and hence to keep all other nuclide peaks at fixed pulse heights. A third possibility is to use a portable multi-channel analyzer to record the entire spectrum, and by subsequent computer analysis, correct the known peaks of the natural radionuclides to their standard positions and calculate their activities.

8.5 Field Trials

After a review of costs, convenience, availability, and required accuracy, a Scintrex GAD-6 stabilized NaI uranium survey spectrometer was selected as providing the best combination of desirable attributes for a field survey instrument. It was rugged, well tested, convenient to use, and a 75 mm x 75 mm detector was sensitive enough to provide soil radium estimates in less than 300 s counting time. Larger detectors are available if shorter counting times are required, and small detectors are available to make measurements down boreholes if the variation in radium with depth is required.

The detector/spectrometer combination was calibrated for measurements at 1 m height at the G.S.C. large pads at Uplands Airport. The calibration constants are shown in Table 5. Results of measurements in a variety of areas and soil types are reported in Appendix 3.

9. SITE EVALUATION PROCEDURES

9.1 Measurement Methods Summary

The surficial soil radium content can be estimated rapidly by gamma spectrometric measurements of the gamma rays from Bi-214. Measurements of this nuclide have been made by airborne detectors over large areas of Canada to estimate the surficial uranium concentration averaged over areas of 10^4 m^2, and maps of this are available.

In areas where there are not outcrops of uraniferous rock to complicate evaluation, soil radium can be estimated directly from these maps. For uraniferous areas, or unmapped areas, satisfactory portable equipment is available to make local measurements to a similar accuracy.

Soil air permeability can be measured both in the field and in the laboratory, but the methods are more suitable as research tools rather than screening tests. The field methods suffer from a great sensitivity to soil moisture content and hence to weather conditions, while the laboratory methods require an 'undisturbed' soil sample and specialized equipment. In general, direct measurement of permeability does not appear attractive as a screening method.

It seems likely that relatively high soil permeabilities are required to cause high radon concentrations in housing, which implies fairly coarse soils containing little clay. This suggests that a more convenient screening test would be an estimation of permeability from more easily measured properties, such as grain size, percent clay, or 'texture'. A number of these properties are plotted on agricultural soil maps for much of Canada, so if a correlation could be developed, the permeabilities of large areas could be estimated from these maps.

9.2 Radon Index Number

A Radon Index Number is suggested as a tool to rate sites on their potential to cause high radon concentrations in houses. The suggested form is

$$\text{Radon Index Number (RIN)} = \log(\text{radium concentration}) + n \log(\text{permeability}) + C_1 + C_2 \ldots + C_m$$

where n is <1, and C_1 depends on annual wind velocity; C_2, annual temperatures; C_3, house type; etc. Sites with a value of RIN less than a critical value will not cause high radon concentrations, and the probability of high radon concentrations can be expected to increase rapidly as the RIN increases above the critical value. Additional work will be required to establish the values of n, C and the critical value of RIN.

9.3 Site Evaluation Methods

The availability of map information on soil radioactivity and soil type or texture suggests that a three-stage evaluation procedure is possible. The first stage would be a regional evaluation, using aerial survey maps and soil maps to estimate the Radon Index Number for a region. Large areas could be identified as acceptable, unacceptable, or requiring further investigation.

The second stage would be an area investigation, where the boundaries of areas could be delineated more accurately than possible from maps covering large areas. Investigation techniques that would be used for this stage would include size analysis of near surface soil samples, and in-situ measurements of soil radioactivity by gamma spectroscopy.

The third and final stage would be a site investigation. This would only be required if the area investigation was not conclusive. Investigation techniques required at this stage would include collection of undisturbed soil cores to a depth of at least 1 m below the footing. The horizontal and vertical air permeability and the radon release of each core would then be measured in the laboratory at standard moisture conditions.

10. CONCLUSIONS

The radon supply rate into a building depends on the soil permeability and the soil radon release rate. Existing instrumentation and methods are adequate to determine these parameters in the laboratory, and to estimate them in the field. Development of new instruments is not required.

It appears possible to derive a Radon Index Number for each site from the soil permeability and radon production rate that is proportional to the expected radon supply rate into a building. The suggested form is

$$\text{Radon Index Number} = \log(\text{radium concentration}) + n \log(\text{permeability}) + C_1 + C_2 + C_3 \ldots + $$

where n is a weighting factor less than 1, and the C's are constants that depend on house type and climate.

11. ADDITIONAL WORK

Before RIN's can be calculated and used on a routine basis, additional work will be necessary to (a) determine the value of the weighting factor n more accurately, and (b) determine the value of RIN above which the radon supply rate starts to be of concern (critical value of RIN).

The value of the weighting factor can best be determined by the use of more elaborate computer models to take into account the effect of the continual fluctuations in wind speed and direction on the pressure distribution around the house.

The critical value of RIN can best be determined by field measurements of soil radon production rate and soil permeability in the vicinity of houses that have a range of known radon entry rates. Correlation of radon supply rate with RIN will provide a check on the validity of the calculated weighting factor, and suggest the value of RIN below which radon is not a concern.

The most tedious part of the determination of RIN for an area will be the measurement of soil permeability. If permeability could be estimated

from mapped soil parameters such as 'texture', the RIN could be simply derived for many areas without the necessity of field work. Additional work to develop a good correlation between air permeability at residual saturation and 'texture' is needed to make the use of Radon Index Numbers a practical proposition for large scale use.

REFERENCES

A-77 Atomic Energy Control Board Information Bulletin 77-2, 1977, 'Criteria for Radioactive Clean-Up in Canada'.

A-78 First Workshop on Radon and Radon Daughters in Urban Communities Associated with Uranium Mining and Processing, Elliot Lake, Ontario, March 7-9, 1978. Sponsored by the Atomic Energy Control Board.

A-79 Second Workshop on Radon and Radon Daughters in Urban Communities Associated with Uranium Mining and Processing, Bancroft, Ontario, March 12-14, 1979. Sponsored by the Atomic Energy Control Board.

A-80 Third Workshop on Radon and Radon Daughters in Urban Communities Associated with Uranium Mining and Processing, Port Hope, Ontario, March 12-14, 1980.

Co-77 Corey, A.T., 1977, 'Mechanics of Heterogenous Fluids in Porous Media', Water Resources Publications, P.O. Box 303, Fort Collins, Colorado.

Cr-77 Ed. Crawford, H.B., 1977, 'Electronic Designers' Handbook, McGraw-Hill, Inc.

Ds-79 DSMA ATCON LTD., 1979, 'Natural Radioactivity in Ontario Sands', Report 7, Atomic Energy Control Board.

Fr-79 Freeze, R.A., Cherry, J.A., 1979 'Groundwater', Prentice-Hall of Canada Ltd.

G-67 Economic Geology Report 24, 1967, 'Groundwater in Canada', Geological Survey of Canada, Department of Mines, Energy and Resources.

Ge-79 Garcia-Bengochea, I., et al, 1979, 'Pore Distribution and Permeability of Silty Clays', J. of Geotechnical Eng. Div., Proc. Am. Soc. Civil Engineers, 105, GT7, 14686.

Je-78 Jensen, C.M., 1978, 'Emanating Power and Diffusion of Radon Through Uranium Mill Tailings', in NEA Seminar on 'Management Stabilization and Environmental Impact of Uranium Mill Tailings', Albuquerque.

REFERENCES - continued

Ma-79 Marshall, T.J., Holmes, J.W., 1979, 'Soil Physics', Cambridge University Press.

St-82 Strong, K.P. and Levins, D.M., 1982, 'Effect of Moisture Content on Radon Emanation from Uranium Ore and Tailings', Health Physics 30, 263-270.

TABLE 1

POROSITY VALUES

Deposit	Porosity (%)	Grain Diameter Range (mm)
Gravel	25-40	>2.0
Sand (coarse)	25-50	2.0 - 0.2
Sand (fine)	30-50	0.2 - 0.02
Silt	35-50	0.02 - 0.002
Clay	40-70	<0.002
Spheres in open packing	48	
Spheres in close packing	26	

TABLE 2

RESIDUAL SATURATION VALUES

Deposit	% Clay (<2 μm)	Porosity (%)	Residual Saturation (%)
Sand	3	40	15
Loam	22	50	58
Clay	47	60	68

TABLE 3

RANGE OF PERMEABILITY VALUES

Deposit	k (cm^2)
Gravel	10^{-3} - 10^{-6}
Clean sand	10^{-5} - 10^{-8}
Silty sand	10^{-6} - 10^{-10}
Silt	10^{-8} - 10^{-12}
Glacial Till	10^{-9} - 10^{-15}
Marine Clay	10^{-12} - 10^{-15}

TABLE 4

RADON ESCAPE FRACTION AND SOIL TYPE

Location	Soil Type	pCi Ra/g	Escape Fraction E (%)
U.S.A. (Je 78)			
Shirley Basin (Wyo)	Clay	6.0	15
	Soil	6.0	10
Powder River (NM)	Clay	2.7	25
	Soil	1.2	40
Ambrosia Lake (NM)	Soil	0.5	25
	Shale	1.2	15
Canada (Ds 79)			
Ontario			
Elliot Lake	Sand (average)	0.8	21
Bancroft	Sand	0.2	15
	Clayey Sand	0.7	15
Holland Marsh	Loam	0.4	15
Niagara Falls	Till	0.7	5
Kettle Point	Clay	7.0	10
Saskatchewan			
Uranium City	Sand	2.0	15

TABLE 5

CALIBRATION CONSTANTS

DETECTOR SCINTREX GSP-35 AT 1 m HEIGHT, SPECTROMETER GAD-6

Sensitivity (counts/sec per pCi/g in soil)

S_T	0.84
S_u (Bi-214)	0.86 (= 0.69 for soil Ra-226)
S_k	0.38

Stripping Constants (counts in Channel 1 per counts in Channel 2)

α (u/Th)	0.79
β (K/Th)	0.8
γ (K/u)	0.64

Backgrounds (count/sec)

B_T	0.1
B_u	0.15
B_k	0.15

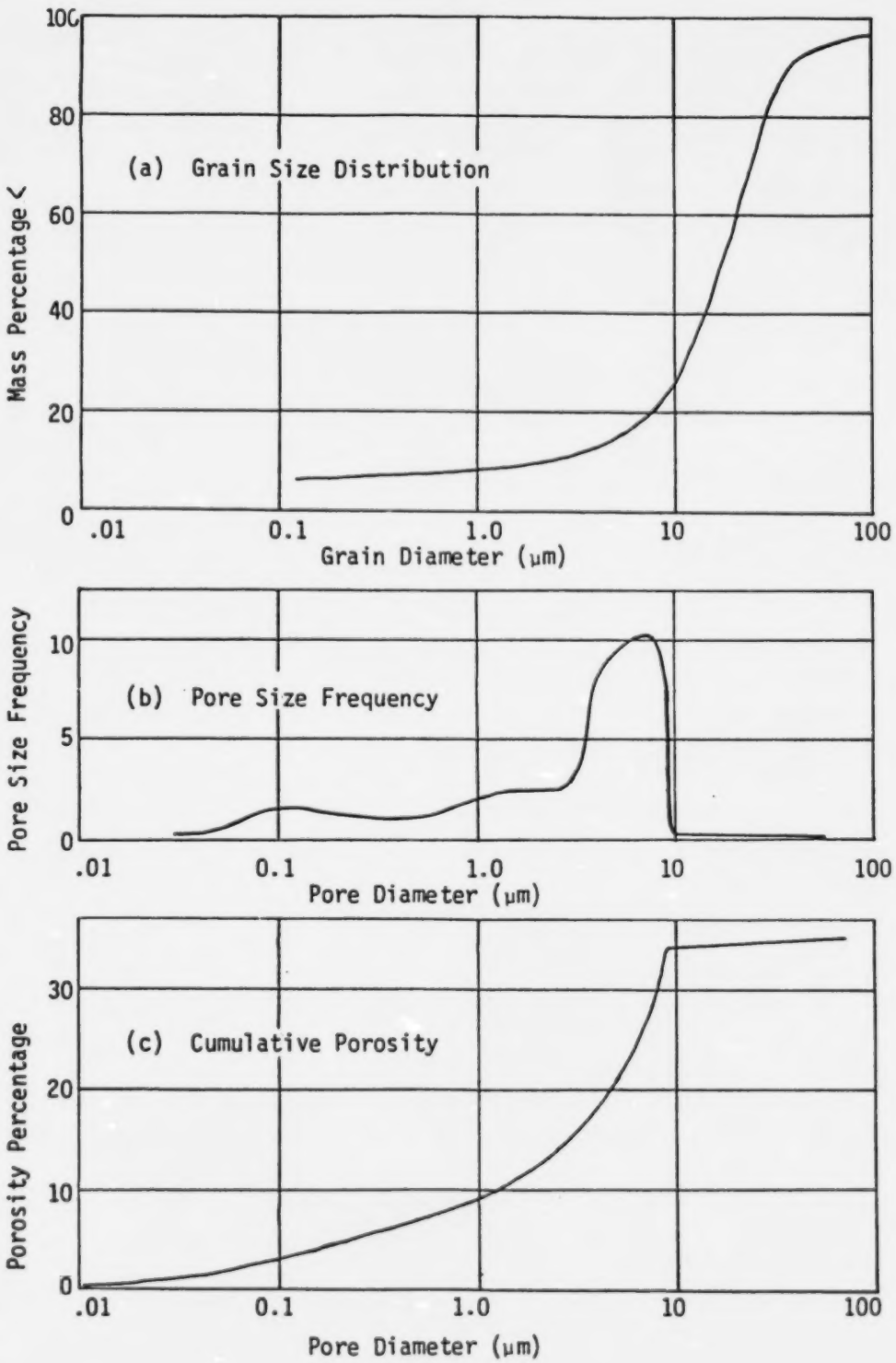


FIGURE 1 GRAIN SIZE AND POROSITY

DSMA ATCON LTD.

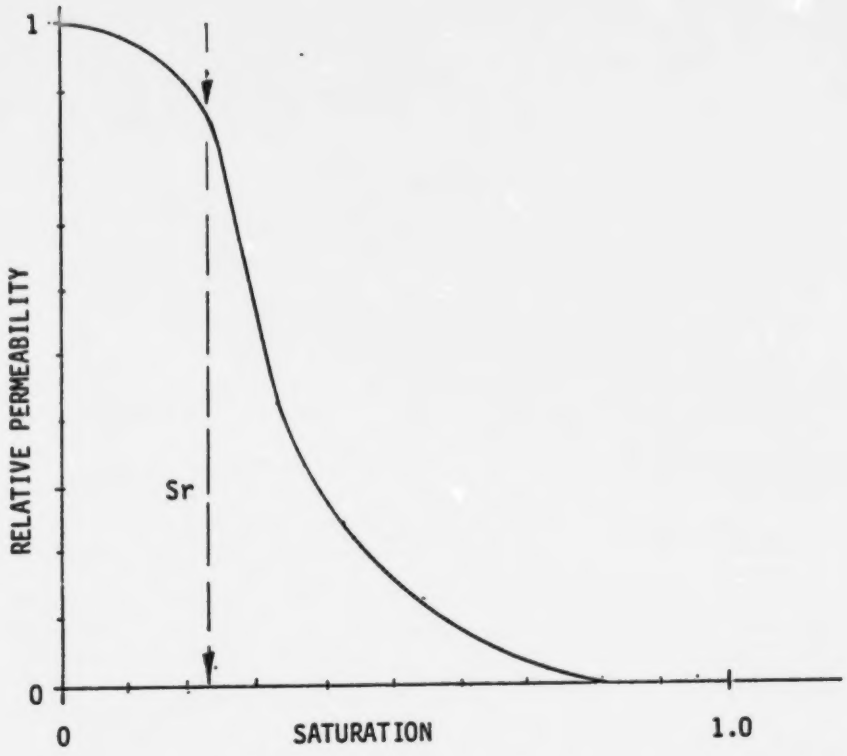
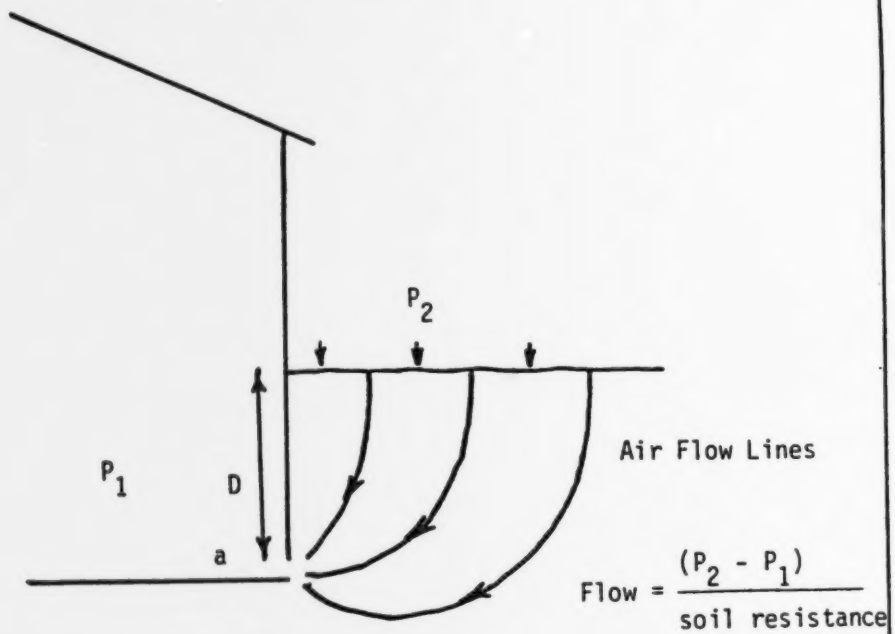
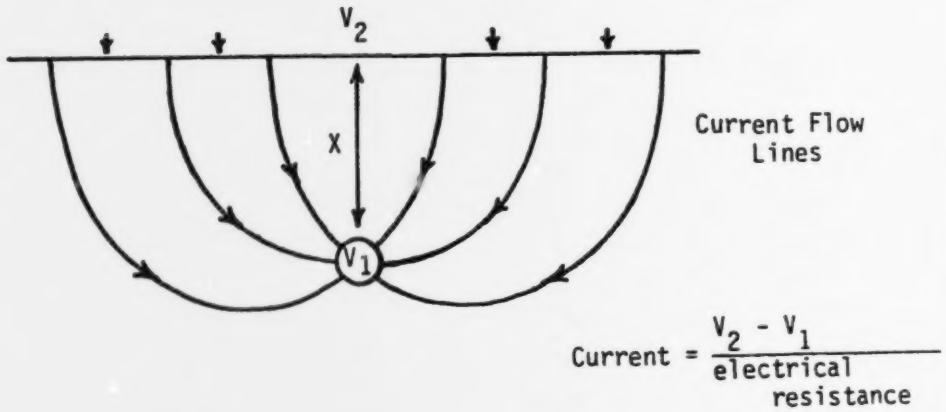


FIGURE 2 TYPICAL VARIATION OF AIR PERMEABILITY WITH SATURATION



A. SOIL AIR FLOW TO A BASEMENT



B. CURRENT FLOW TO A LINE CONDUCTOR

FIGURE 3 AIR AND CURRENT FLOW

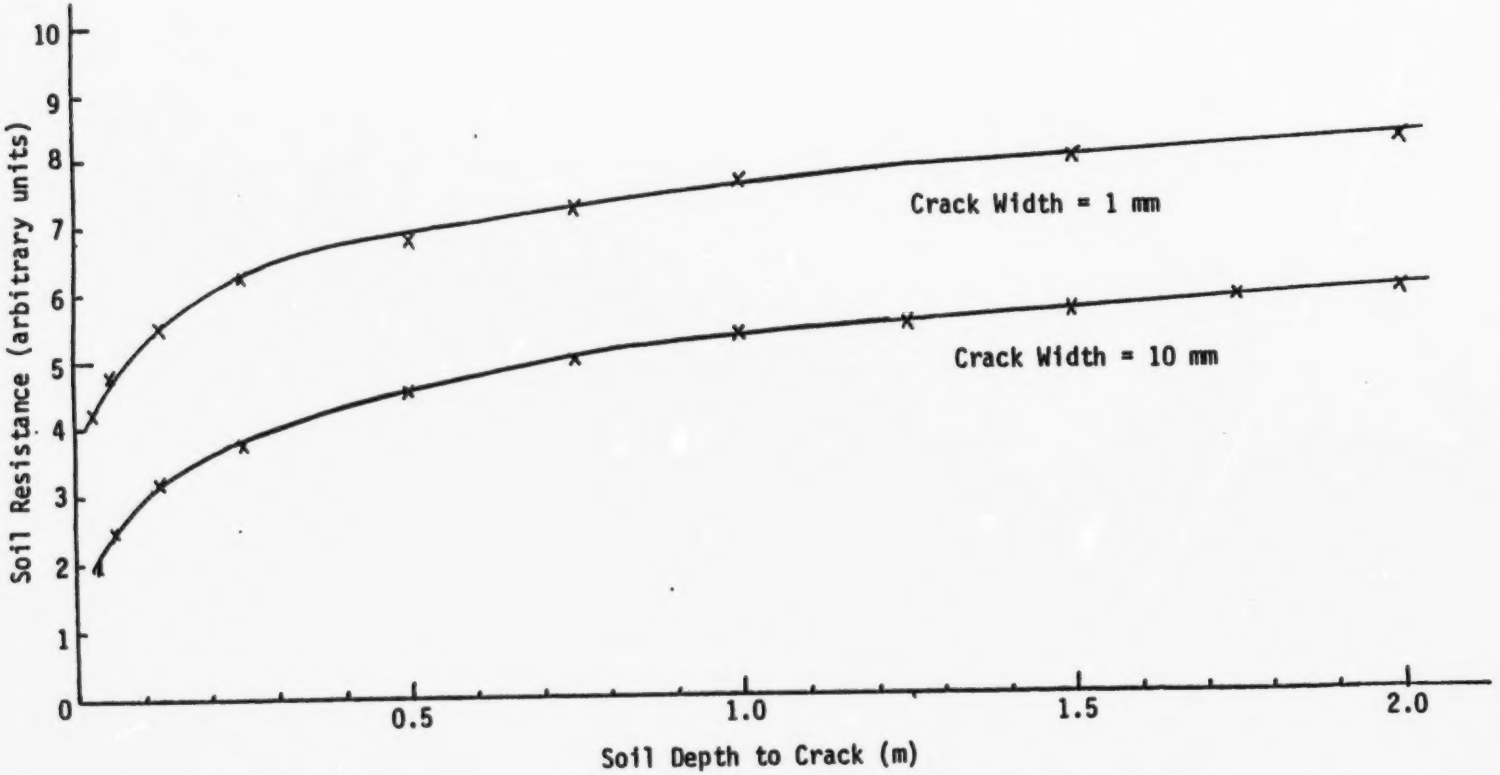
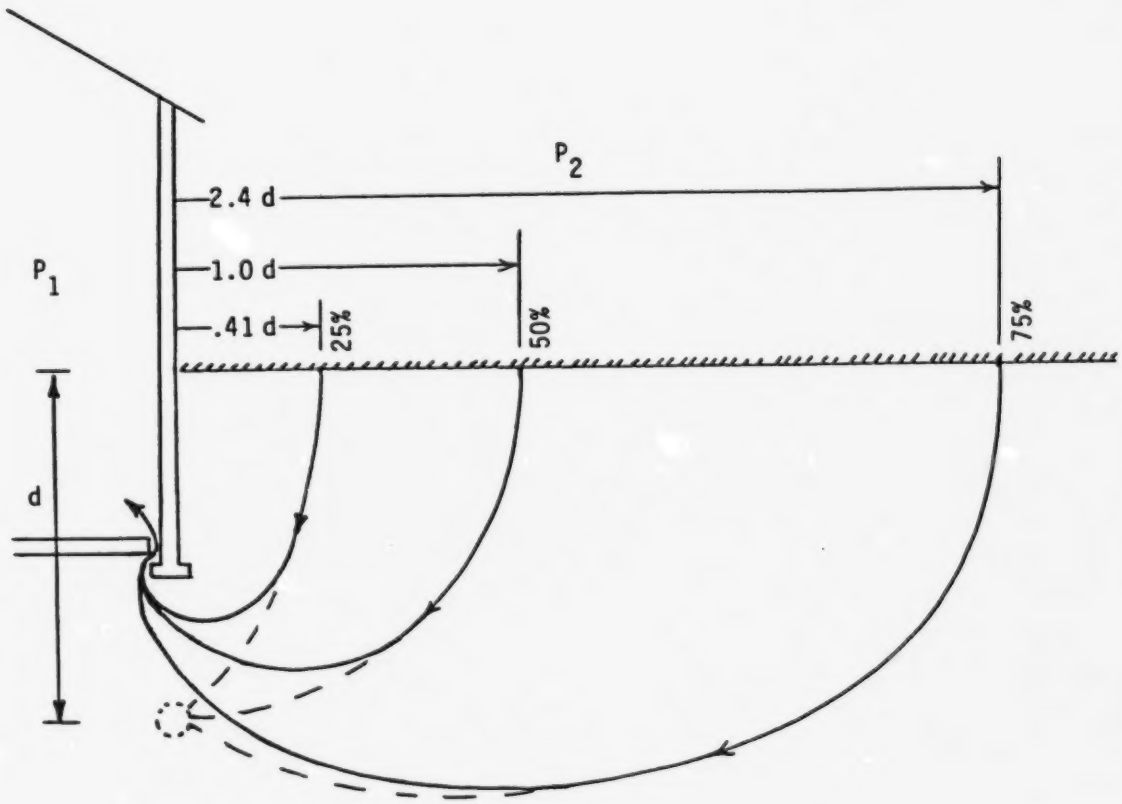


FIGURE 4 - AIR FLOW RESISTANCE AS A FUNCTION OF DEPTH

DSMA ATCON LTD.



P: Pressure
d: Effective Depth

FIGURE 5 DISTRIBUTION OF SOIL AIR FLOW

DSMA ATCON LTD.

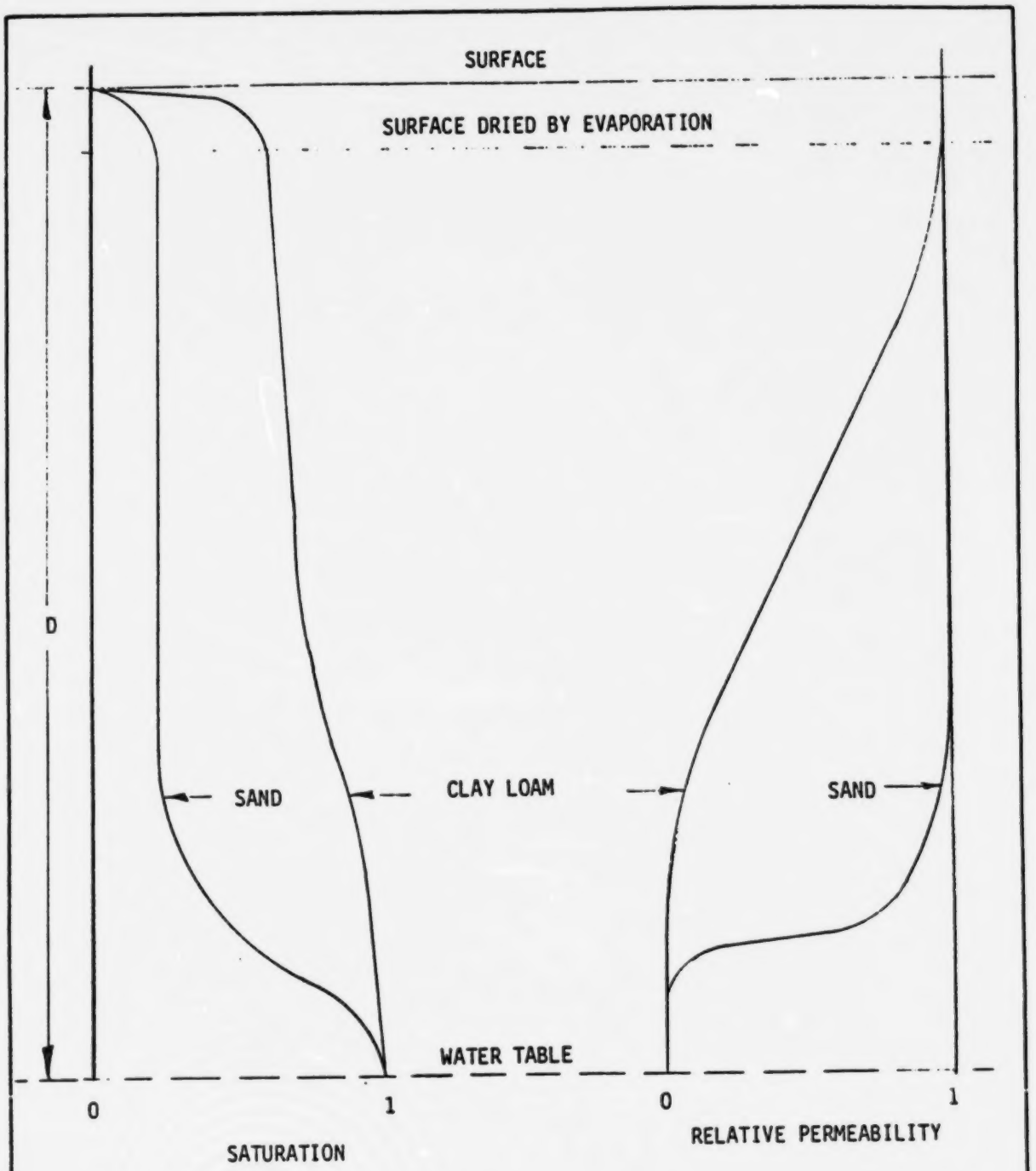


FIGURE 6 VARIATION OF SOIL MOISTURE AND PERMEABILITY WITH DEPTH

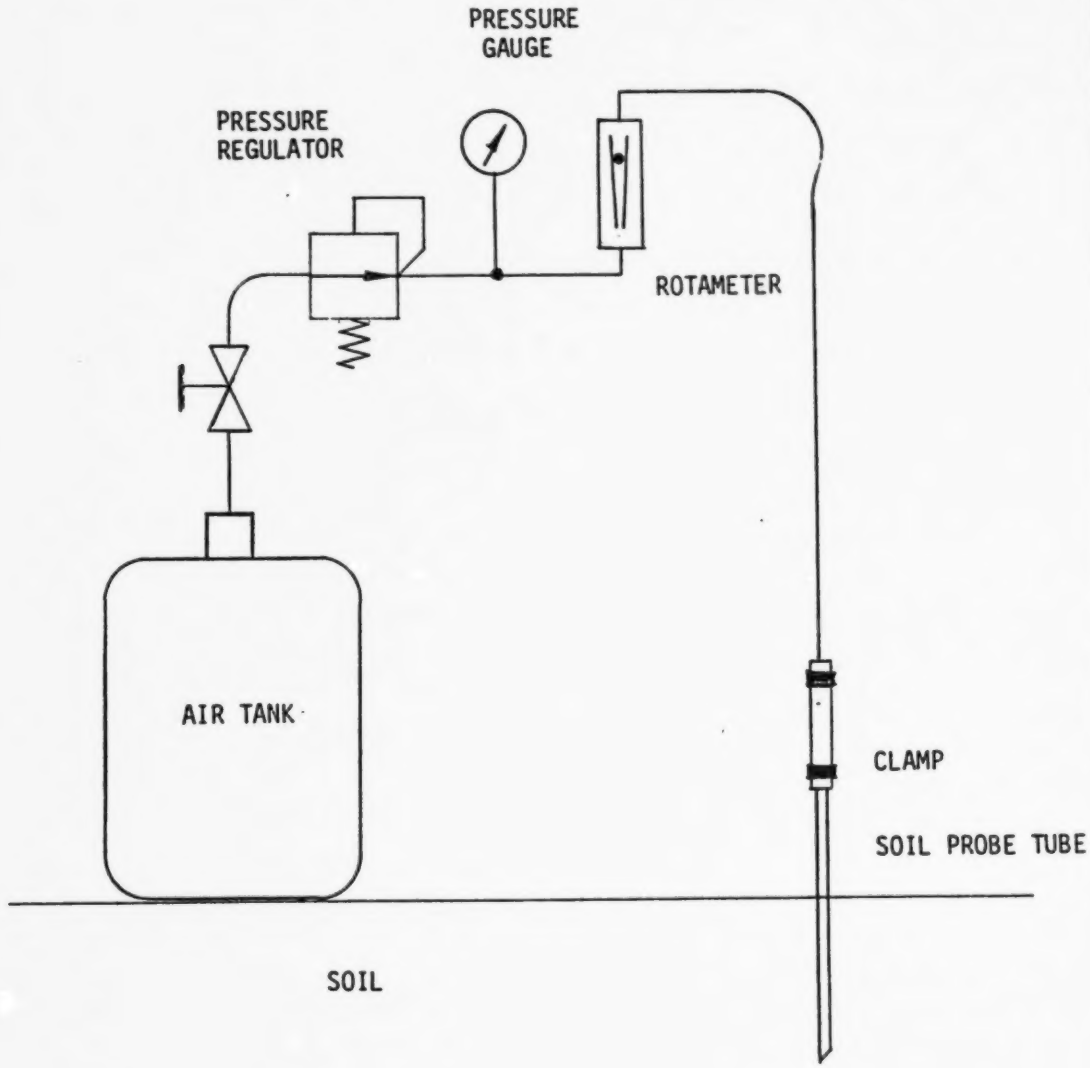
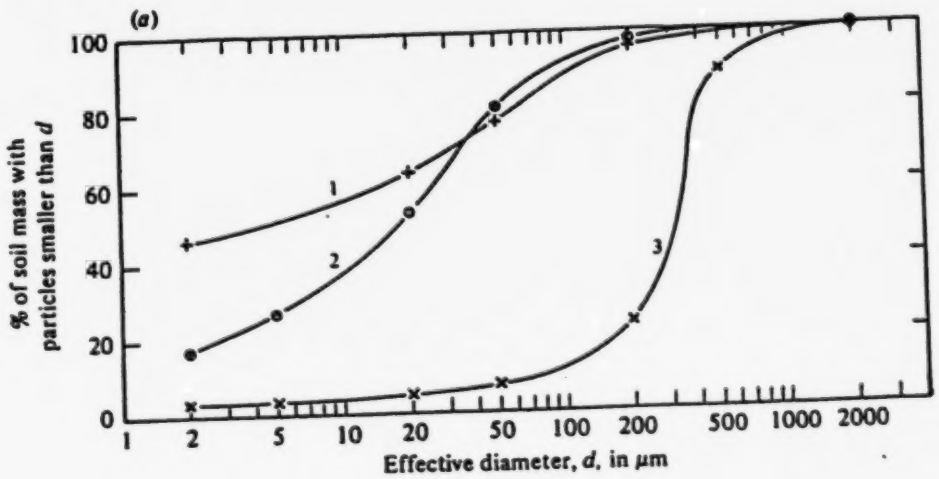
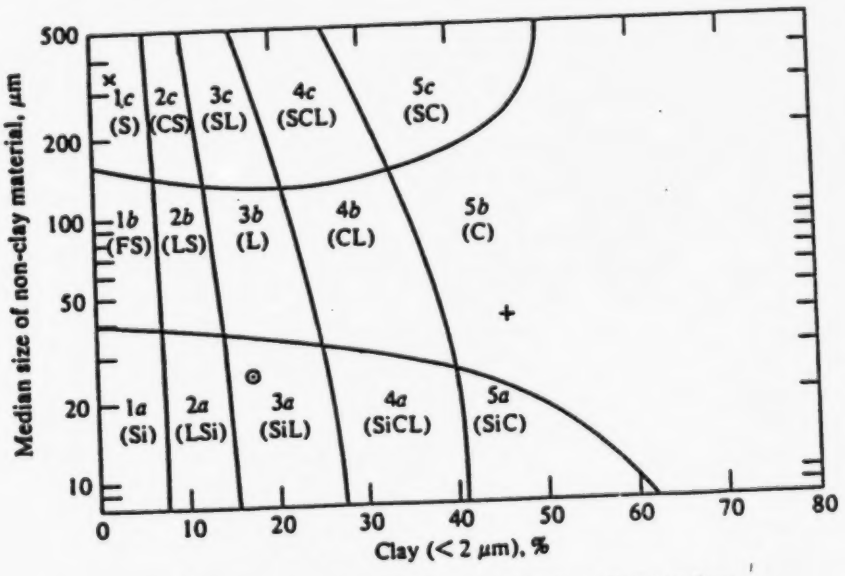


FIGURE 7 SOIL PERMEAMETER

DSMA ATCON LTD.



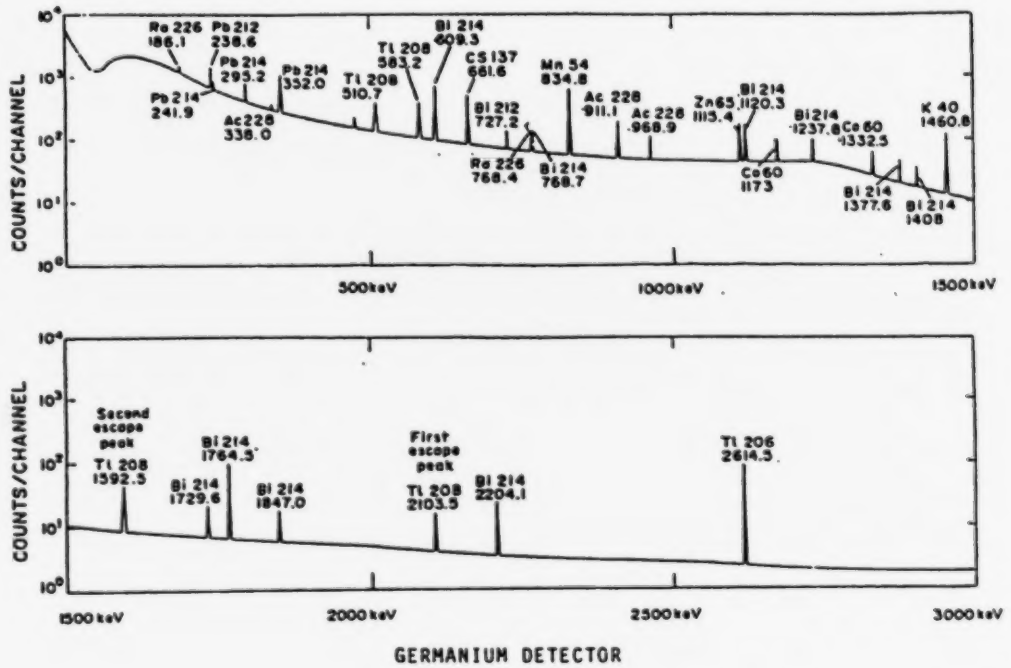
Particle size analysis. (*a*) Cumulative curves for three soils with textures of (1) clay, (2) silty loam and (3) sand.



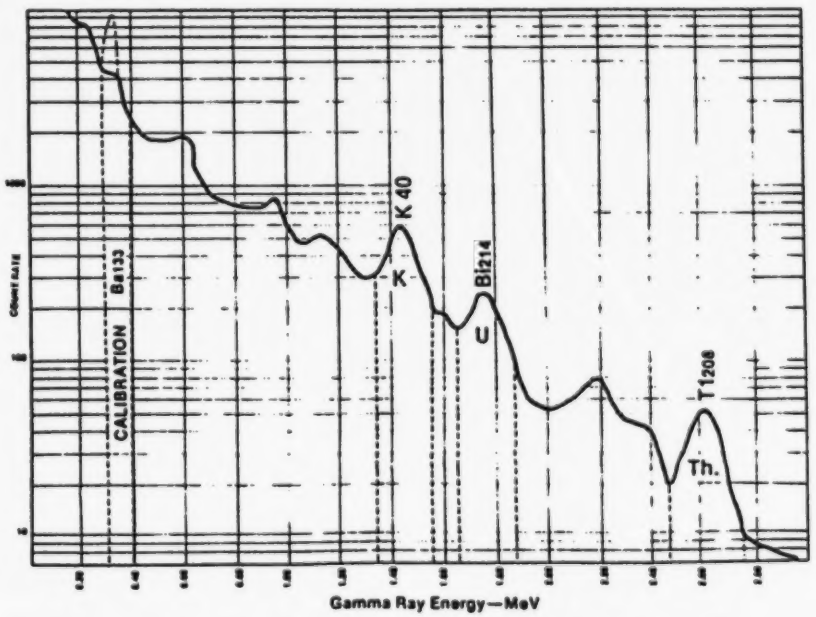
Relation between texture and particle size distribution.

Texture diagram in which particles larger than 2 μm are represented by an average size (Marshall, 1947). (F = fine, S = sand(y), Si = silt(y), C = clay(ey), L = loam(y). Plotted points represent the three soils of Fig. (*a*))

FIGURE 8 SIZE DISTRIBUTION AND TEXTURE



GERMANIUM DETECTOR



SODIUM IODIDE DETECTOR

FIGURE 9 SPECTRAL COMPARISON OF ENVIRONMENTAL RADIATION AS OBSERVED BY A GERMANIUM AND A SODIUM IODIDE DETECTOR

DSMA ATCON LTD.

APPENDIX I

REFERENCE LIST FOR SOIL PERMEABILITY MEASUREMENT

1. Blight, G.E., 1971, 'Flow of Air Through Soils', Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 97, SM4, 607.

2. Evans, D.D. and Kirkham, D., 1949, 'Measurement of the Air Permeability of the Soil in Situ', Soil Sci. Soc. American Proc., Vol. 14, 65.

3. Grover, B.L., 1955, 'Simplified Air Permeameters for Soil in Place', Soil Sci. Soc. American Proc., Vol. 19, 414.

4. Goring, C.I.A. and Hamaker, J.W., Ed: 1972, 'Organic Chemicals in the Soil Environment', Pub. Marcel Dekker, Inc. N.Y.

5. Kirkham, D., 1946, 'Field Method for Determination of Air Permeability of Soil in its Undisturbed State', Soil Sci. Soc. Amer. Proc., Vol. 11, 93.

6. 'Proceedings of the Conference on In-Situ Measurement of Soil Properties', 1976, Amer. Soc. Civ. Eng., New York, N.Y., U.S.A.

7. Maasland, M. and Kirkham, D., 1955, 'Theory and Measurement of Anisotropic Air Permeability in Soil', Soil Sci. Soc. Amer. Proc., Vol. 19, 395.

8. Pall, R., and Moshenin, N.N., 1980, 'Permeability of Porous Media as a Function of Porosity and Particle Size Distribution', Trans. ASAE 1980, 742.

9. Ragab, R, Feyen, J. and Hillel, D., 1981, 'Comparative Study of Numerical and Laboratory Methods for Determining the Hydraulic Conductivity of a Sand', Soil Science, Vol. 131, 375.

10. Sonu, J. and Movel-Seytoux, J., 1976, 'Water and Air Movement in a Bounded Deep Homogenous Soil', J. Hydrol, Vol. 29, 23.

11. Steinbrenner, E.C., 1959, 'A Portable Air Permeameter for Forest Soils', Soil Soc. Amer. Proc., Vol. 23, 478.

12. Van Groenenwond, H., 1968, 'Methods and Apparatus for Measuring Air Permeability of the Soil', Soil Science, Vol. 106, 275.

APPENDIX II

COMPUTER MODELLING OF THE MOVEMENT OF RADON THROUGH SOIL INTO HOUSES

1. INTRODUCTION

Radon is carried into houses by the movement of soil gas through the soil into the basement. As the pressure differentials are low, the gas flow velocities are low, and there is a limit to the distance from which radon can be collected before the wind direction changes and changes the pressure and flow distribution around the house. This type of problem cannot be solved analytically, so it was examined using a finite difference computer model to calculate the radon supply rate into a house basement as a function of time and the surface pressure distribution.

2. MODEL DESCRIPTION

The model represents a cross-section through the soil at right angles to an infinitely long basement. The section extends to 6 metres on either side of the basement, and to 1.6 m below the basement footings. The basement has 3 openings in the floor, representing the wall-floor joint at each wall, and central floor crack along the length of the basement.

The soil is simulated by an array of 626 variable sized elements, which range from 10 x 10 cm square near the basement up to 120 x 80 cm irregular quadralaterals at the edges of the model remote from the basement.

The pressure distribution in the soil resulting from a surface pressure distribution is calculated by applying Darcy's Law to each element and solving the set of simultaneous equations for the pressures by an iterative process. Once the pressure distribution in the soil is found, the flows from element to element can be calculated by Darcy's Law.

3. SURFACE PRESSURE DISTRIBUTIONS

The surface pressure distributions considered were similar to those produced by the wind and thermal forces around a 6 m high house with basement.

The wind pressure on the ground upwind of the house is assumed to increase linearly from zero at a distance of 3 m to the stagnation pressure at the house wall. The downwind ground suction is assumed to fall linearly

from -0.7 stagnation pressure at the house wall to zero at 30 m downwind. The wind direction and speed are assumed to be constant, so the pressure distributions are fixed in time. Leakage from the house is taken to decrease the house pressure by 0.7 Pa.

The pressure differential due to the stack effect is calculated on the basis that the ground temperature is constant at $5^{o}C$, interior temperature at $20^{o}C$,exterior temperature constant at $-10^{o}C$, and that the neutral plane is 3.5 m above the basement floor.

Three pressure surface distributions were considered.

1. 15 km/h wind from right to left - 10 Pa stagnation pressure + stack effect
2. 15 km/h wind from left to right - 10 Pa stagnation pressure + stack effect
3. Stack effect alone -3.3 Pa.

4. SOIL PRESSURE DISTRIBUTION

The pressure and flow distribution comes rapidly to equilibrium with the surface pressure distributions. The change of flow through a basement crack following in a sudden change in pressure was simulated, and the time constant, $t = 1.25 \times 10^{-5}\ \theta/k$ seconds, where θ = porosity, and k is permeability (cm^2). Accordingly, a change in surface pressure distribution produces a new soil pressure distribution within a few minutes in the permeable soils that allow significant radon entry rates. Soil gas travel velocities are only a few cm/h, so changes in the soil pressure distribution can be regarded as taking place instantly as far as the movement of radon is concerned.

5. RADON MOVEMENT

As the soil gas moves through the soil, the radon contained in it decays, and additional radon is released into the soil gas from the soil through which it passes. The radon concentration in an element of the model is therefore set by the amount of radon carried in from adjacent elements, the release rate of radon from the soil in the element, the porosity of the soil, and the gas flow through the element. As the element

to element flows are known when the pressure distribution has been calculated, the radon concentrations as a function of time can be calculated for any pressure distribution.

6. ILLUSTRATION

Figure 1A shows a vertical cross-section through the soil and basement and the pressure distribution produced in the soil by surface pressure distribution #1. The upwind pressure zone extends through the soil, and is distorted underneath the house by the presence of the highly permeable subfloor fill layer. The pressure in the fill is slightly above the pressure in the house at the upwind floor crack and the central floor crack, so air containing radon flows into the basement. The pressure in the fill is slightly below the house pressure at the downwind floor crack, so air flows out of the basement into the soil.

If these flows were maintained for several days they would produce the pattern of radon concentrations shown in Figure 1B. The flow of air from the upwind soil surface to the basement floor crack has reduced the radon concentrations in the soil within 1 m of the basement wall and the reduced concentration zone extends to the west floor crack. A similar reduced concentration zone has been produced in the soil at the downwind end of the floor, due to airflow out of the basement at the east floor crack.

7. RESULTS

The effect of changing wind directions on the radon distribution near the house was simulated by cyclically applying the pressure distribution for the west wind for 7 hours, the stack effect (equivalent to north wind) for 6 hours , the east wind for 5 hours, and the stack effect (equivalent to south wind) for 6 hours. A quasi-equilibrium state was reached after a few cycles, and the variation of radon supply rate through each opening in the floor slab is shown in Figure 2.

When the wind blows from the west, air flows out of the east floor crack, reducing that radon supply to zero. When the wind blows from the

north or south, so just the stack effect operates, soil gas flows in through all openings. As the radon concentration in the soil has been reduced by air moving out of the downwind openings, when the pressure changes the radon supply through those openings starts at zero, and increases slowly. The pressure difference at the central floor crack and the radon concentration is almost constant, so the radon supply through that crack is almost constant.

The wind blows more from the west than from the east, so the radon concentration in the soil adjacent to the east floor crack is slightly lower. This is shown by the lower supply rates when the east wind blows, even though the soil gas volume flows are the same as when the west wind blows.

The effect of soil porosity on radon supply is shown in Figure 3, which shows the total radon supplies calculated from soil permeabilities of 10^{-7} cm^2 and 10^{-6} cm^2. Although both supply rates are variable, the average supply rate at 10^{-6} cm^2 is equivalent to 4.5×10^5 pCi/h, and at 10^{-7} cm^2 is 1.0×10^5 pCi/h. An increase by a factor of 10 in permeability produces an increase of 4.5 in radon supply, suggesting that the weighting factor for radon permeability in the Radon Index Number is about 0.7.

A radon supply of 5×10^6 pCi/h into a typical house will produce radon concentrations in excess of 5 pCi/h, so these results suggest that significant radon concentrations in houses will occur only where the soil permeability is in excess of 10^{-6} cm^2, and the soil radium production rate is more than 0.4 pCi/g emanating radium (1 pCi/g total radium).

The computer model used for these calculations is relatively simple, with a severely limited range of surface pressure distributions. However, as the model dimensions, pressure distributions, and permeabilities are similar to those found around houses, we can expect the results to be a reasonable approximation to reality.

More realistic models would take into account at least the three dimensional nature of the soil surrounding the basement; the complex surface pressure distribution produced around a house when the wind is not at right angles to the walls; and the changes of soil permeability caused by changes in soil moisture and frost. It is only by modelling these changes that we can hope to measure their influence on radon movement into houses, and understand how they influence the calculation of Radon Index Number.

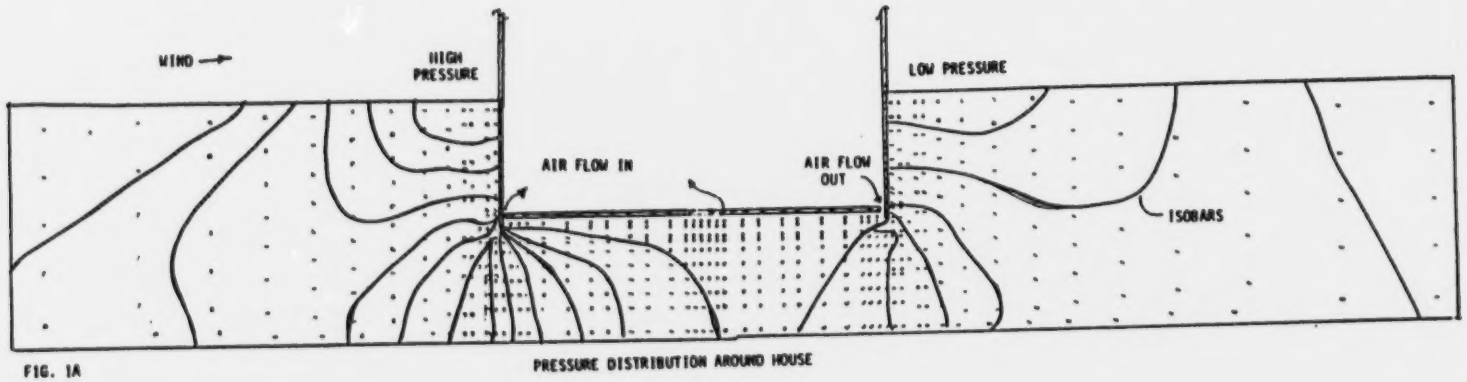


FIG. 1A

PRESSURE DISTRIBUTION AROUND HOUSE

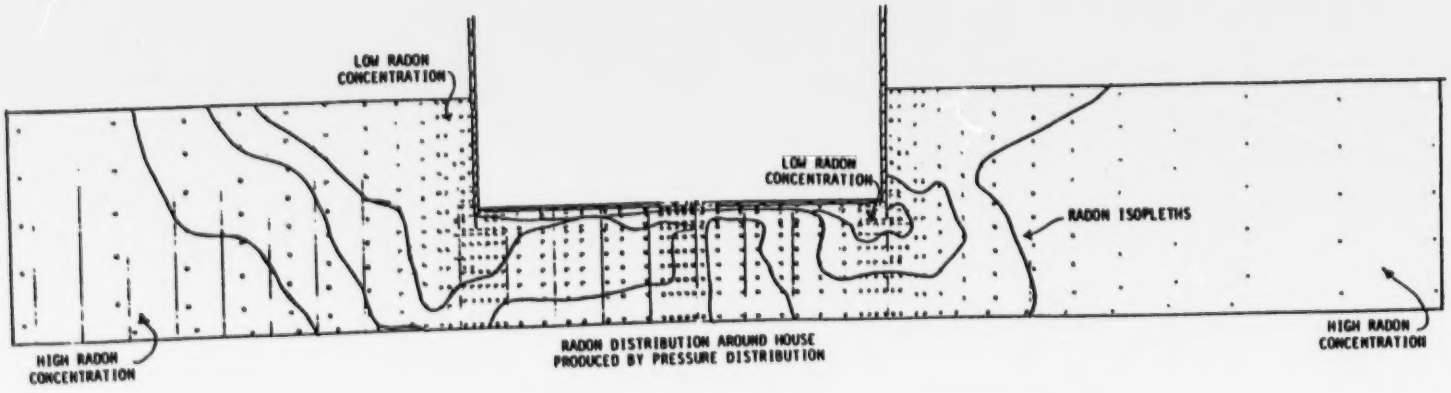


FIG. 1B

RADON DISTRIBUTION AROUND HOUSE PRODUCED BY PRESSURE DISTRIBUTION

FIGURE 1 COMPUTER GENERATED PRESSURE AND RADON DISTRIBUTIONS

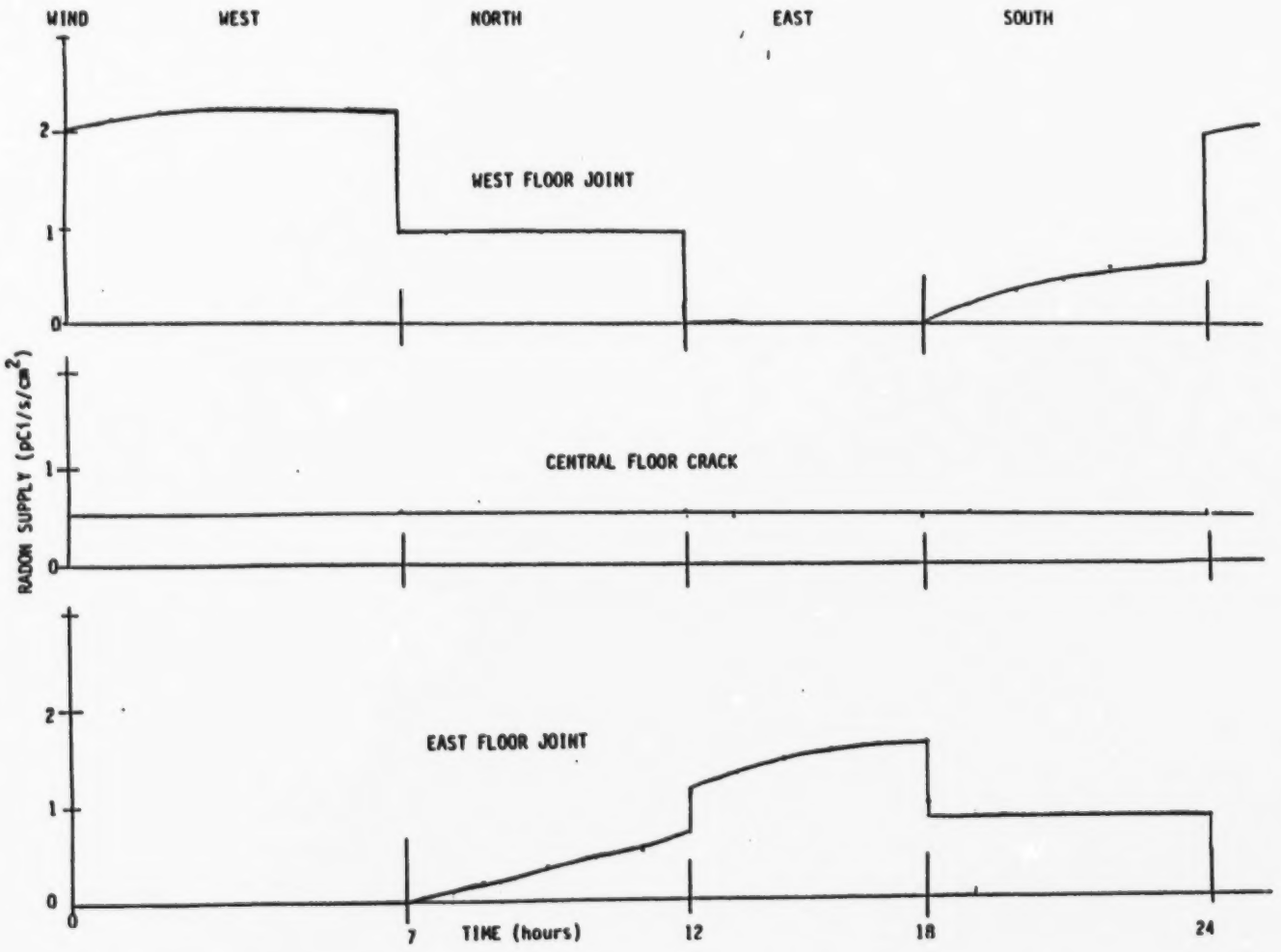


FIGURE 2 VARIATION IN RADON SUPPLY RATE THROUGH EACH FLOOR OPENING

DSMA ATCON LTD.

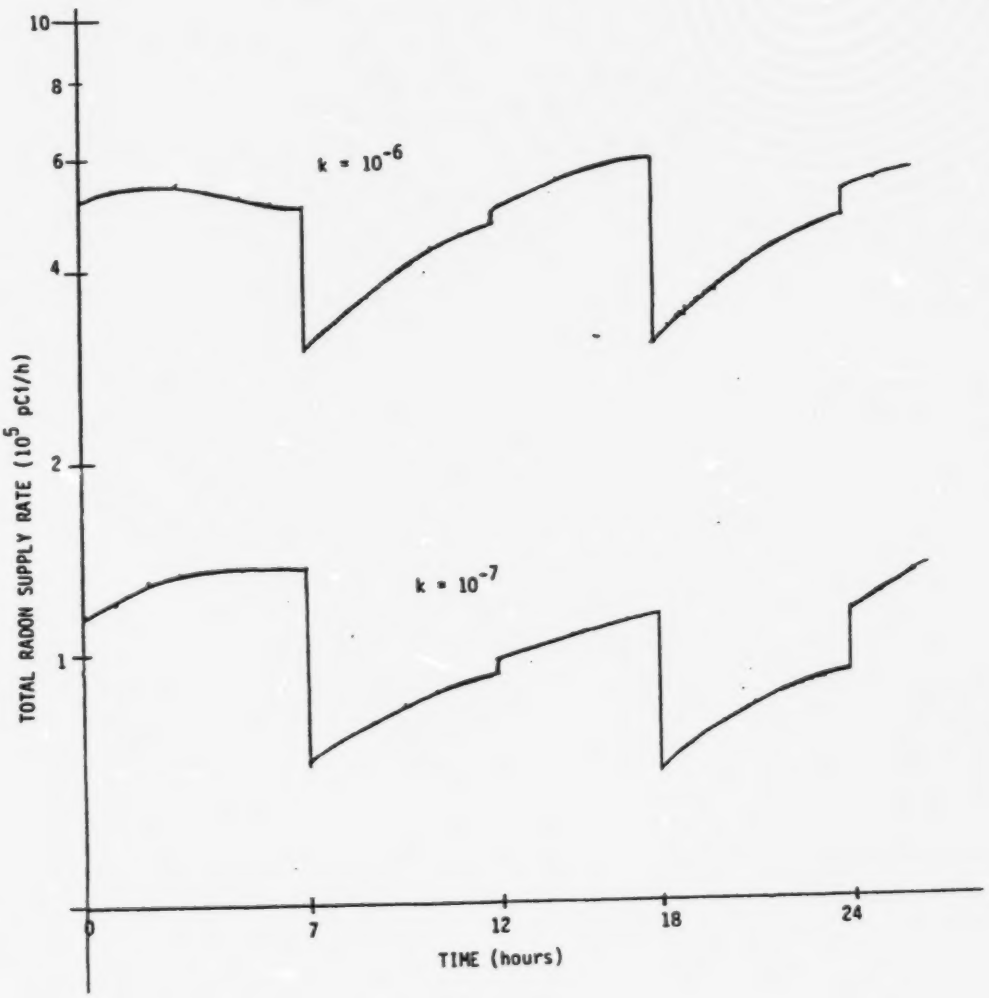


FIGURE 3 VARIATION IN TOTAL RADON SUPPLY RATE

APPENDIX III

FIELD TRIP REPORT

1. FIELD EVALUATION OF EQUIPMENT

A field trip was made to evaluate the utility of an in-situ porosity meter in conjunction with a NaI 3 channel spectrometer as a method to predict the potential of sites to give elevated radon levels in houses. Comparisons were made between areas of known low radon concentrations in housing such as Southern Ontario and areas of known high radon concentrations in housing such as Bancroft. Measurements were also made in the South March area near Ottawa. Table AIII-1 shows the measured near surface radionuclide concentrations and permeability.

2. EQUIPMENT PERFORMANCE

2.1 Radiation Measurement

Operation of the 3 channel spectrometer equipment was trouble-free as would be expected from this well developed piece of field equipment. The aluminum stand (not part of the original equipment) used to support the detector at 1 m height was found to be insufficiently stable to prevent the detector being blown over in high and gusty winds. A more stable stand with a permanent mounting bracket would be required for routine use.

The 75 mm x 75 mm NaI detector was sensitive enough to measure uranium and thorium concentrations of less than 0.2 pCi/g with counting times of 300 seconds, which was more than adequate to measure the concentrations met within the environment. Larger, and more cumbersome, detectors would only be required if it was intended to survey large areas using this equipment, and it was important to reduce the time spent per measurement. Use of a 15 cm x 10 cm detector (available from this manufacturer) would give similar sensitivity with counting times of 30 seconds, increasing the productivity of the equipment.

Calibration factors for the detector at 1 m height were obtained at the G.S.C. large area calibration pads at Uplands Airport, and are given in Table II.

2.2 In-Situ Permeameter

Operation of the in-situ permeameter was relatively trouble-free. The flow meter and pressure gauge gave no trouble, although a wider range of pressures and flows would have been helpful, as most measurements tended to the extremes of the measurement range. The probe and mandrel combination could only be driven into soils that did not contain significant amounts of pebbles or rocks. If they were present, it was not possible to drive the probe deep enough (20 cm) to get even an approximate value of permeability.

Measurements were made under the unfavourable conditions of a melting snow fall, so the upper soil layers had relatively high saturations. In some cases there was sufficient water present to completely prevent the flow of air into soil - especially in the heavier soils.

Visual evaluation of soil texture at the same time as the samples were taken suggested that soil permeability could be estimated nearly as well by that method as by the permeameter. Low permeabilities were associated with cohesive soils containing significant clays, and high values were associated with loose sandy soils with small amounts of clay. Surface soil samples could be obtained easily even in areas where the stony nature of the ground prevented insertion of a permeameter probe, suggesting that estimation of permeability from 'texture' might be a more satisfactory field approach than use of a field permeameter.

TABLE AIII-1

RADIOACTIVITY AND PERMEABILITY

Location	Th pCi/g	U pCi/g	K pCi/g	'k' cm^2	Comment
Mississauga	0.9	1.0	15	$<10^{-10}$	Clay
Mississauga	0.8	0.7	11	10^{-10}	Wet loam
Mississauga Lakeshore	0.4	0.4	10	$7x10^{-10}$	Wet sandy loam
Rice Lake	0.4	0.4	11	$<2x10^{-10}$	Wet sandy loam
#7-28 Junction	0.7	0.4	10	$<10^{-10}$	Wet loam field
Peterborough	0.7	0.6	12	$<10^{-10}$	Wet loam field
#6-28 Junction	0.7	0.5	13	$5x10^{-8}$	Roadside gravel pit
Apsley	0.7	0.4	15	$1x10^{-9}$	Meadow
Dyno Estates	1.3	1.0	19	$2x10^{-8}$	Gravel pit
S. Paudash	0.8	0.5	15	$5x10^{-9}$	
Cardiff	1.0	0.7	20	--	---
Paudash	0.9	0.7	17	$9x10^{-8}$	Meadow
Faraday Mine Area	1.8	1.5	19	--	Rock outcrop
Bancroft	1.7	0.6	23	Could not drive - large stones, gravel pit	
Bancroft	7.1	3.6	14	--	Rock outcrop
Bancroft	2.2	1.3	15	$<10^{-10}$	Gravel area (wet)
York River	0.7	0.5	14	$9x10^{-11}$	Meadow - wet
S. Maynooth	0.7	0.7	14	$9x10^{-8}$	Gravel
S. Maynooth	0.5	0.4	13	--	Rock outcrop
Maynooth Station	0.6	0.9	13	$1x10^{-8}$	
Maple Leaf	0.7	0.6	16	$2.5x10^{-9}$	
Barnes Bay	0.6	0.5	21	$9x10^{-8}$	
Killaloe	0.7	0.3	18	$<10^{-10}$	Wet
Eganville	3.0	1.4	21	--	Rock outcrop
March Township					
McCurdy Drive	0.7	0.4	15	$9x10^{-9}$	Park
McCurdy Drive	0.5	0.5	15	$6x10^{-9}$	Undisturbed soil
McCurdy Drive	0.5	0.5	11	Could not drive - too rocky	
Ottawa Airport	0.5	0.8	15	--	Grass

APPENDIX IV

ENVIRONMENTAL GAMMA SPECTROSCOPY EQUIPMENT

APPROXIMATE PRICES

NaI Spectrometers

GeoMetrics

GR410	$ 6,500
345 cm^3 Detector	4,000
1845 cm^3 Detector	10,000

Scintrex

GAD-6	8,000
390 cm^3 Detector	4,500

McPhar

Spectra-44 + 345 cm^3 Detector	8,500

Urtec

UG-140	3,000
345 cm^3 Detector	3,500
2000 cm^3 Detector	8,000

Typical Package Price = $8,000 - $12,000

Ge Spectrometers

Portable Multi-channel Analyzer

Canberra Series 10	$13,000
Davidson 2056	12,000
Mobilizer III	10,000
Nuclear Data ND6	15,000

Portable Ge Detector

20 cm^3 effective volume	15,000
40 cm^3 effective volume	20,000
120 cm^3 effective volume	30,000

Typical Package Price = $35,000

geoMetrics

PORTABLE GAMMA RAY SPECTROMETER MODEL GR-410

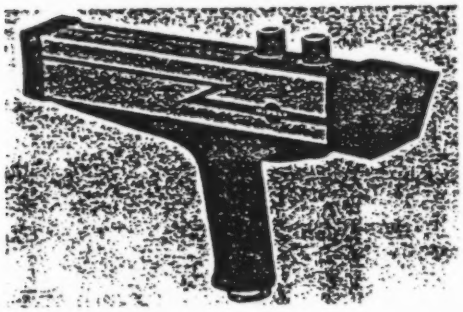
- ★ **Simultaneous four-channel differential measurement of potassium (^{40}K), uranium (^{214}Bi), thorium (^{208}Tl) and total count (T/C) — Pushbutton operation**
- ★ **Versatility — Field portable, helicopter, truck, borehole and laboratory detectors — no console modification required**
- ★ **Digital sampling for selectable time periods provides optimum count statistics even for weakly radiating sources**
- ★ **Data outputs — Sequential 4-digit display of accumulated countrates for each channel; front panel analog ratemeter; analog recording; audio alarm of countrates above background**
- ★ **Internal reference isotope automatically checks PMT gain to assure calibration accuracy — prevents marginal data even during rapid temperature changes.**
- ★ **Accurate calibration and stripping constants for rapid field assay of uranium, thorium and potassium**
- ★ **Front panel "Function Indicator" tells user all important operating conditions at a glance**
- ★ **Compact, weatherproof, rugged console — simplified controls — operation on "D" cell flashlight batteries**

The Model GR-410 is a differential four-channel portable gamma ray spectrometer with applications versatility never before possible from such a compact console. Ruggedly engineered for accurate, simultaneous measurements of potassium (^{40}K), uranium (^{214}Bi), thorium (^{208}Tl) and the total energy spectrum. The GR-410 provides a sequential unambiguous digital display of each channel, a front panel ratemeter and analog output for single channel recording. Standard operational features include pushbutton measurements at selectable time periods, a dual purpose audio alarm, an internal reference isotope for simple in-field calibration, a visual alphanumeric indicator of operating functions and compatability with a variety of plug-in detectors. Our lightweight 21.2 cu. in. (0.35 l) hand-held detector is ideal for field exploration and other detectors are available up to 256 cu. in. (4.2 l) for helicopter, truck and laboratory applications. Complete borehole probes and accessories are also offered for natural gamma logging. The GR-410 is a reliable, lightweight spectrometer that utilizes advanced circuit components and features operation from common "D" cell flashlight batteries. Controls and displays provide simple operation and clear readability; no special operating skills are required.

The GR-410 is an excellent tool for uranium prospecting, geologic mapping, ground follow-up of larger airborne radiometric surveys, natural gamma logging, property and mine site evaluation, and numerous sampling and assay requirements.

© 1978 geoMetrics

McPHAR RADIOMETRICS

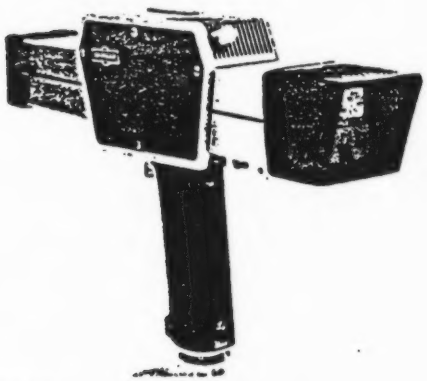


TC-33A

TC-33A

Portable Gamma Ray Scintillometer

Internal 1.5" x 1.5" (3.8 x 3.8 cm) detector
Variable pitch audio alarm
Ratemeter range switch selectable 100, 300, 1000, 3000, 10,000 C.P.S.
Weight 3 lbs. (1.4 Kg.), batteries included
Energy response – total count, all energy above .2 Mev
Power source – two "C" cell batteries
Temperature range (-35 to +55° C)

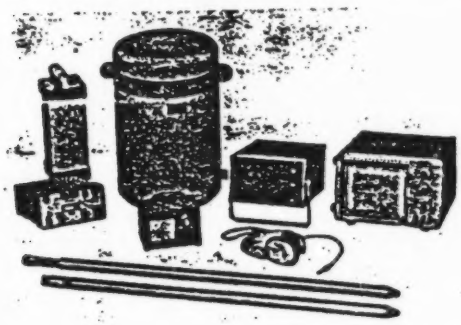


TV-1A

TV-1A

Portable 3 Channel Gamma Ray Spectrometer

Internal 1.5" x 1.5" (3.8 x 3.8 cm) detector
Three threshold settings – total count, uranium + thorium, thorium
Adjustable audio alarm
Ratemeter range switch selectable 100, 1000, 10,000, 100,000 C.P.M.
Power source – two "C" cell batteries
Weight – 4 lbs. (1.8 Kg.) batteries included
Voltage regulated to ½ initial battery voltage
Temperature range (-35 to +55° C)



Spectra-44, 3" x 3" detector, 6" x 4" detector, single channel recorder, audio system, and borehole logging detectors.

Spectra-44

4 Channel Differential Gamma Ray Spectrometer

Reads in both analogue and digital mode
Provides individual readings of: total count, K-40, Tl-208 and Bi-214
Multi-functional as ground, drill-hole, mobile, marine and airborne system
Meter and 4 digit sequential readout
Sample time – 1-30 seconds/minutes in 8 steps
Energy response – 0.4 to 2.8 mev
Power source – 12 "D" size alkaline batteries
Console weight, with batteries – 8.5 lbs. (3.8 Kg.)
Temperature range (-25 to +55° C)
Probe unit – standard 3" x 3" (7.6 x 7.6 cm) external. For additional detector systems for use with SPECTRA-44, please refer to section below.

SCINTREX GAD-6 Stabilized Four Channel Gamma-ray Spectrometer

Function

The GAD-6 is a portable, digital, four channel spectrometer designed for use with a range of Scintrex gamma-ray sensors. It is of the same basic design as its successful predecessor, the GAD-4, with the important addition of spectrum stabilization to overcome any drift problems due to temperature and countrate variations which are encountered in field work.

The GAD-6 can provide quantitative analysis for K, U and Th content in outcrop, drillhole, laboratory, mobile ground or airborne survey applications.

The GAD-6 allows both integral or differential gamma-ray energy analysis with digital counting of four channels simultaneously. Compton stripping can be done automatically and stripping factors can be dialed in digitally. A front panel switch permits selection of stripped or unstripped output. By another switch selection, output values can be automatically normalized to counts per second. Simultaneous four channel analogue and BCD digital outputs make the GAD-6 a full-fledged airborne spectrometer.

The GAD-6 electronic console may be complemented by the GSP-4S (2.5" x 2.5", 360 cm^3) portable sensor, which contains an NaI (Tℓ) crystal, photomultiplier, high voltage supply and radioisotope source. Alternatively, larger crystal volumes available in the GSA-61 (1.8ℓ), GSA-41 (4.2ℓ), GSA-42 (8.4ℓ) or GSA-44 (16.8ℓ) sensor package can be used for ground mobile or airborne surveys. The GAD-6 is easily coupled to the GSD-4S drillhole sensor which is supplied complete with cable and winch.

In situ analysis of radioactive outcrops or drill-holes can be carried out using threshold or differential measurements. Depending on crystal size and counting times, sensitivities better than 50 ppm are obtainable for uranium and thorium and better than 1% for ^{40}K content. Such assays are extremely useful for property evaluation, grade control and identification of rock lithologies. Since the output data can be automatically Compton stripped, outputs in the U channel are directly proportional to eU_3O_8. The operator needs only to apply a constant for the source-detector geometry in order to calculate equivalent uranium values.

Features

Portable, airborne or ground mobile applications.

Simultaneous counting of four channels.

Spectrum stabilization permits calibration in the morning and all day, drift-free operation for temperature and countrate variations which may be encountered under field conditions.

Compton stripping function with easily dialed in stripping factors.

Differential or integral energy analysis with preset Total Count, K, U or Th window or threshold settings.

Up-to-date digital nuclear pulse handling techniques ensure precise uranium, thorium and potassium differentiation.

Advanced CMOS and integrated circuitry are used throughout for accuracy, low temperature coefficient and excellent long term stability.

High countrate capability ensures a gain drift of less than 0.3% at an input rate of 20K cps when tested with a random pulse generator producing pulses equivalent to 1 MeV.

Excellent pulse pair resolution reduces the dead time to less than 3% at a countrate of 20K cps.

Low power consumption circuitry permits long battery life using six standard 'D' cells.

Five digit display minimizes the possibility of overflow counts.

For mobile or drillhole surveying four analogue and digital outputs are available simultaneously for use with chart or digital recorders.

There are eight switch selectable sampling times ranging from 1 to 3000 seconds, increasing in a statistically meaningful logarithmic fashion. In addition, the sampling time can be externally controlled.

The visual output can be automatically normalized in counts per second regardless of the accumulation time. This reduces operator error to a minimum.

Switch selection permits the operator to read the digital output of four channels sequentially or to select any one of the four channels. This saves time and prevents errors in cases where all four channel values are not required.

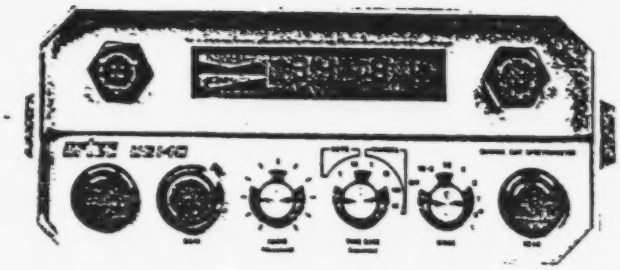
Any value can be called up repeatedly at any time after the counting has been completed simply by depressing a button. The values are only erased when a new counting period is begun. Counting and visual display can be stopped and re-started at any time.

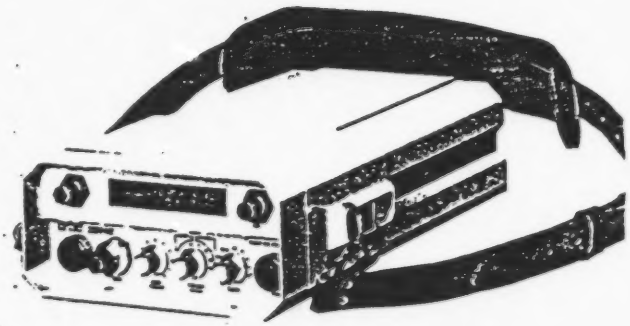
UG-140

PORTABLE GAMMA RAY SPECTROMETER

FEATURES:

- **SIX CHANNELS** — Two total count plus Potassium (40K) Uranium (214Bi), Thorium (208Tl) and one enhanced Uranium channel.
- **ENHANCED URANIUM CHANNEL** — Combines the most pronounced (214Bi) photo-peaks for enhanced uranium discrimination.
- **INTERNAL OR EXTERNAL DETECTOR** — Basic unit is supplied with an internal detector and built in provision to interface an external detector.
- **LARGE CRYSTAL DETECTOR** — Internal detector provides (9 cu. in. — 148 cc).
- **VERSATILITY OF APPLICATION** — Unit can be used as portable, mobile, or airborne spectrometer with large volume external detectors.
- **CONTINUOUS GAIN MONITOR** (Calibration) — Internal reference isotope with continuous gain status display.
- **DEDICATED LCD DISPLAY** — Multifunction LCD display continuously monitors various functions.
- **SNAP-ON BATTERY CARTRIDGES** — Two aluminium cast cartridges provide safe, rapid and waterproof storage and replacement of batteries.
- **WIDE DYNAMIC RANGE** — 1 to 50000cps allows unit to be effectively used with large crystal volumes.
- **AUDIO ALARM** — Frequency response proportional to count rate with selectable and variable background threshold setting.
- **VARIABLE SAMPLE RATES** — Automatic sampling at 1 and 10 seconds. Manual sampling at 1, 10, 100 and 1000 seconds.
- **ANALOG OUTPUT** — Switch selectable for all channels.
- **RUGGED CAST FRAME** — Aluminium cast frame with water sealed controls.





The model UG-140 is a high performance portable differential spectrometer designed with special features which allows the unit to be effectively used as a portable spectrometer with an internally mounted detector or used in mobile or airborne surveys with larger volume external detectors and external power sources.

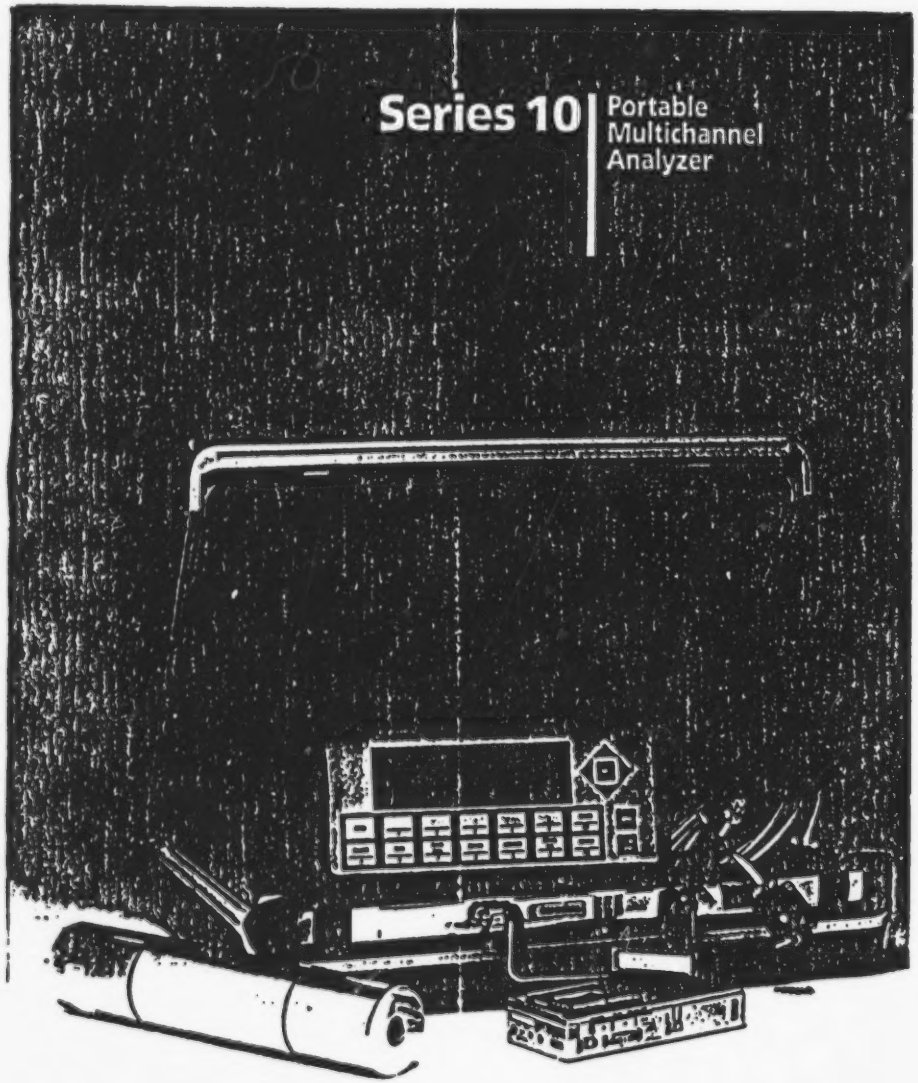
The unit offers a 9.0 cu. in. (148cc) detector with six channels of information including an enhanced uranium channel for more accurate discrimination of (214 Bi).

As a portable gamma ray spectrometer the UG-140 is a compact, rugged instrument designed for rapid evaluation of Potassium (40k), Uranium (214Bi), and Thorium (208T1). The unit is equally suited for rapid reconnaissance prospecting using either of the two total count channels, or for detailed analysis of K.U.T. as a follow up of air-borne surveys, geological mapping, detailed ground surveys or drill core analysis.

The unit ruggedness is derived from a single piece aluminium cast frame with sealed controls and aluminium cast snap-on battery cartridges.

The UG-140 is supplied with a built in calibration source, leather carrying shoulder strap, batteries, operations manual and shipping/carrying case.

Series 10 Portable Multichannel Analyzer

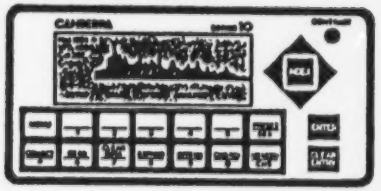


CANBERRA

Friendly.

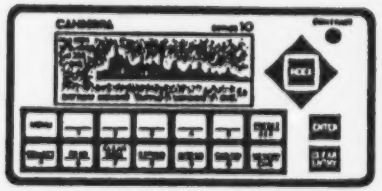
During setup and operation, unique Series 10 features let you concentrate on data analysis without the usual instrument distractions.

ONE BUTTON OPERATION



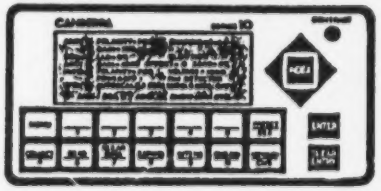
The Series 10, with its menu driven operation and soft keys is designed to be operated at the push of a single button. In the field, a technician need only push the "analyze" soft key to execute an entire analysis sequence. At the end of the data collection, a meaningful result will be calculated and displayed.

BUILT IN DIAGNOSTICS



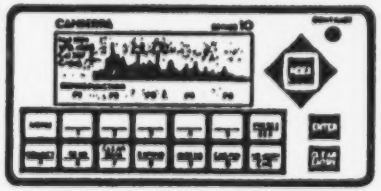
Quality assurance is a snap with menu driven diagnostics. The Series 10 self diagnostics not only checks the condition of the memory, it also verifies all of the hardware including the power supply, amplifier, ADC and batteries at the push of a button. Canberra self diagnostics add a new dimension to portable spectroscopy systems.

INSTANT PARAMETER VERIFICATION



Instant display of all setup parameters is available at the push of a button. No longer do you have to step through an entire setup procedure to check one parameter. Once displayed, any parameter can be changed by going directly to that soft key. In research applications, the Series 10 offers not only superior performance, but the flexibility and ease of operation that allows you to concentrate on the experiment, not on the instrument.

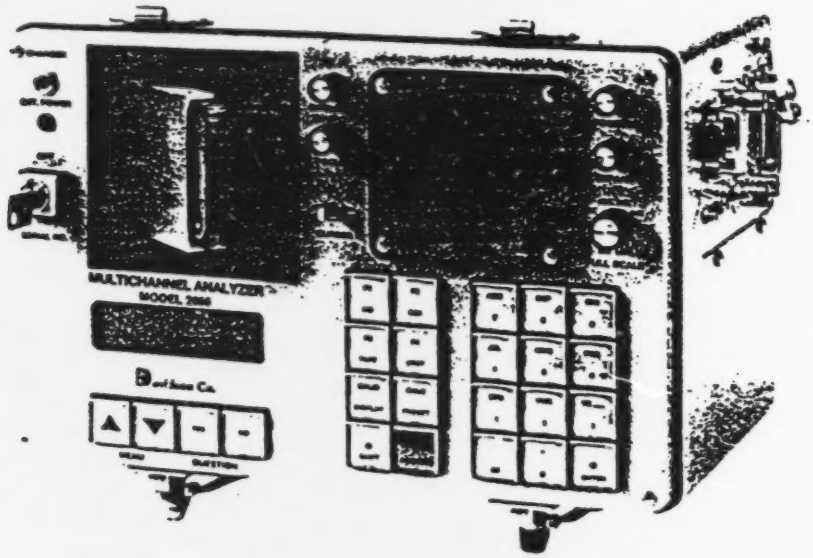
APPLICATIONS-SPECIFIC ANALYSIS



Need custom analysis capability? With the Series 10 you can actually define your own analysis equations and sequences in the field. Whether you're exploring for new energy resources or checking thyroids for iodine, the Series 10 is for you.

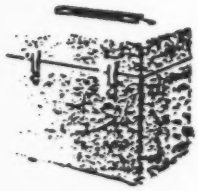
Product Specifications

Model 2056
Portable Multi-Channel Analyzer



FEATURES:

- ☐ 50 MHz ADC
- ☐ 2048 Channels
- ☐ Spectroscopy Amplifier
- ☐ Live CRT Display
- ☐ 24 Key Entry
  - Alphanumeric
  - Control
  - Special Functions
  - Diagnostics
- ☐ Alphanumeric LCD Display
- ☐ Real-Time Clock
- ☐ Digital Data Cassette Recorder
- ☐ RS 232C Serial Interface
- ☐ Detector HV Bias Supplies
- ☐ Software Developed for International Safeguards Program by Los Alamos National Lab

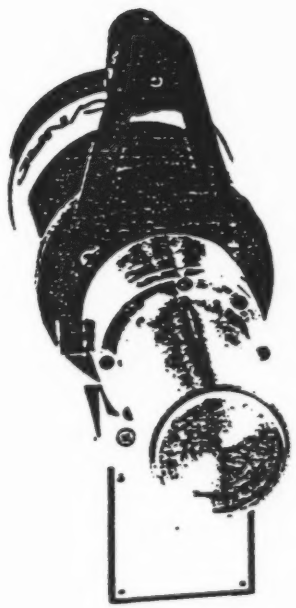


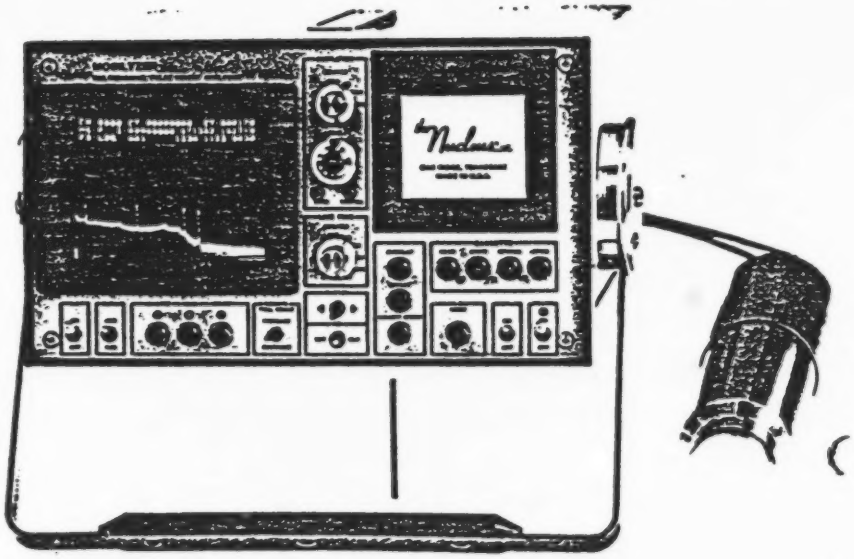
- ☐ Battery Powered
- ☐ 16 Pounds,

(detail specifications on rev

EG&G INSTRUMENTS
EG&G Canada Ltd.
436 LIMESTONE CRESCENT
DOWNSVIEW (TORONTO) ONTARIO
CANADA M3J 2S4
TELEPHONE: (416) 663-6230
TELEX: 06-22694

Davidson Company
19 Bernhard Road • North Haven, Connecticut 06473 • (203) 288-7324





PORTABLE

The MOBILYZER combines many of the features found in laboratory multichannel analyzers with full portability. The unit is rugged, lightweight and battery powered, in fact completely self-contained.

For field use the internal batteries provide many hours of trouble free operation between recharging, and mobile installations are simple, just connect the MOBILYZER to the 12V vehicle electrical system.

In the laboratory, the battery charger provides enough current to operate the MOBILYZER and recharge the internal battery — no need to worry about power outages, the internal battery will take over immediately without losing a single data point.

FLEXIBLE

Available in three versions, the MOBILYZER can cover a wide range of detectors and measurement requirements.

MOBILYZER III with 4096 channel ADC and memory is designed for high resolution spectroscopy. This model contains a spectroscopy grade amplifier, 5000V detector bias with remote shutdown, and preamplifier power to handle a wide range of portable HpGe detectors.

MOBILYZER II with 2048 channel ADC and memory can be supplied with a choice of spectroscopy amplifier or preamplifier/amplifier and either the 5000V or 1500V bias supply depending on your particular needs.

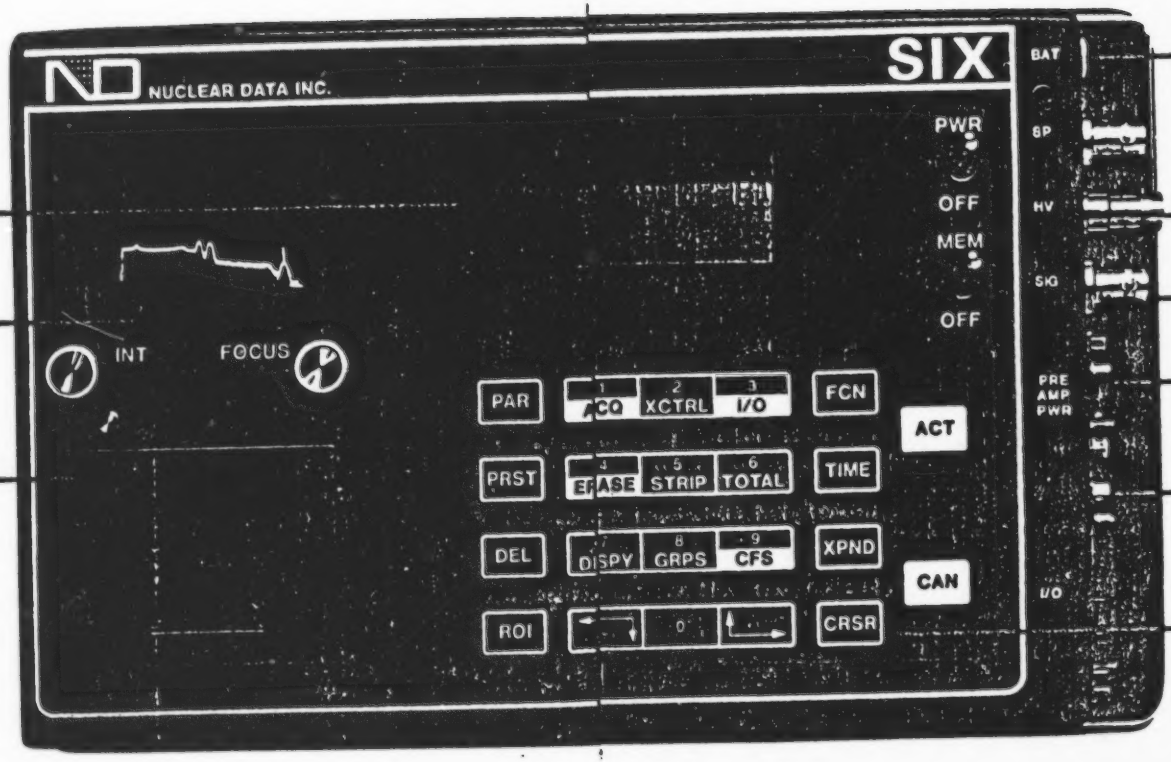
MOBILYZER I with 1024 channel ADC and memory is ideally suited to Sodium Iodide detectors. This version has available as standard the preamplifier/amplifier and 500-1500V high voltage supply with 1W of output power for a variety of PMT bases.

POWERFUL

Even in its standard configuration, the MOBILYZER offers many powerful features such as multiple ROI's, serial output, external control and built-in minicassette tape for data storage. When supplied with the removable keypad option, programmable date and time-of-day clock, spectrum labeling and a unique recycle feature are also included.

This sequence allows preset counting time, output to tape or I/O ports, erase, incrementing spectrum code, wait-time and number of cycles. Simply program the analyzer and it will automatically acquire and store the data at defined intervals.

An addition to keypad is the data manipulation software package. This provides transfer, smoothing and stripping functions for normalizing, subtraction and comparison applications.



Liquid Crystal Display
(LCD)
Keyboard interaction
Parameter display
Time of day/year clock

Data Display
7-cm diagonal)
2048 channels
ROI s intensified
Dual markers for ROI identification
Cursor for energy calibration and readout

Digital Cassette
Permits storage of both spectral data and experiment related parameters (amplifier gain, detector HV, etc) and subsequent read back of either or both into the ND SIX Thus, once the proper set-up parameters for a particular experiment have been stored on cassette, the experiment can be easily repeated at any time

Stores up to five 2K spectra per side of cassette

Battery Charger
Permits simultaneous operation from ac line power and battery recharge

Detector High Voltage Power Supply
±4000 Vdc 225 μA to 1 kV
100 μA above 1 kV

Signal Input

Detector Preamp Power Supply
±12 Vdc, 30 mA for resistive feedback preamplifier

Serial I/O Connector
RS 232-C 2400 baud max
Permits external computer communications and control NDACP communications protocol

User Keyboard
(tactile feedback)
Error-proof entry sequence with prompt from LCD display

The ND SIX...

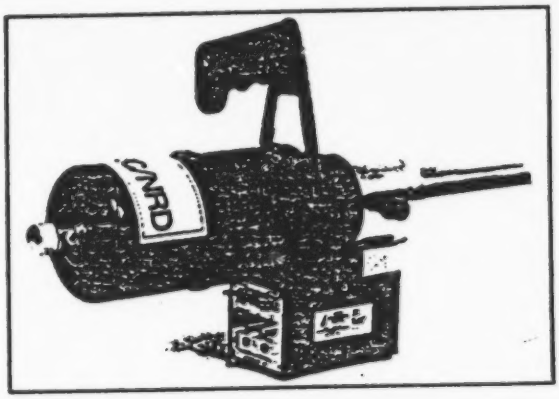
APTEC

Multi-Attitude Portable Detector: Model MAP-101

Features

- May be operated in any orientation
- Lightweight hand held unit
- Liquid nitrogen "sponge" minimizes LN rate of consumption
- Auto-Bias module combines preamplifier, high voltage bias, and detector protection (with visual indication)
- Available with planar or coaxial high purity germanium detectors

Options include:
- Battery Pack for portable operation
- Internal radiation backshielding
- Slim profile snout lengths of 7.6 or 11.6 inches
- 31 liter transfer dewar



Description

The MAP-101 is a truly portable high purity germanium detector incorporating a unique lightweight dewar and cryostat system to allow operation at any orientation. The dewar is filled with a sponge-like material which absorbs the liquid nitrogen. This prevents sloshing and spilling which extends the dewar holding time. The Auto-Bias module provides bias to the detector, a low noise spectroscopy preamplifier, and built-in detector protection (with visual indication) due to:

1) loss of or low liquid nitrogen
2) excessive detector noise
3) excessive countrate

In combination with the shoulder mounted battery pack (option), the MAP may be easily moved around to virtually any monitoring site. Only a single coaxial cable is required to interface with a remote data acquisition system.

The basic MAP includes a coaxial or planar detector, Auto-Bias module, 5.6 inch long endcap, and a lightweight dewar with a molded carrying handle. The MAP has been designed in a modular fashion with a wide variety of options to allow you to customize the detector for your specific requirements.

Specifications

DETECTOR — Any standard PHYGE coaxial or planar detector.
PREAMPLIFIER — Model SP104 Auto Bias (HVPS/Preamp) Module. Standard Preamps (SP101, SP102, or SP103) are available as options.
DEWAR CAPACITY — 0.75 liters.
DEWAR FILLING TIME — Approximately 30 minutes
COOL-DOWN TIME — 2-6 hours (detector size dependent)
HOLDING TIME — 12-16 hours (detector size dependent)
OVERALL LENGTH — 20 inches (planar), 21 inches (coaxial)
SLIM PROFILE SNOUT — planar ..... 5.6 inches long x 2.75 inch diameter
— coax ..... 6 inches long x 2.75 inch diameter
WEIGHT (detector size dependent) — 11 lbs (empty), 12.5 lbs (full)

APTEC NUCLEAR INC. 210 SOUTH 8TH STREET, LEWISTON, NEW YORK 14092 TELEPHONE: (716) 754-7401
APTEC ENGINEERING LTD. 4251 STEELES AVE. W., DOWNSVIEW, CANADA, M3N 1V7 TELEPHONE: (416) 661-9722

NEW 24-Hour Holding Time Gamma Gage™

THE GAMMA GAGE
Portable, Solid-State HPGe Gamma-Ray Spectrometer

- **Portable gamma-ray spectrometer (now available in two sizes)**
- **8- or 24-hour holding time**
- **Available with GEM, GMX, SLP, or GLP detectors**
- **Lightweight**
  <8 pounds for 8-hour holding time
  <11 pounds for 24-hour holding time
- **Automatic high-voltage shutoff protection**
- **Withstands 100% humidity, non-condensing**
- **All-attitude operation**
- **High-count rate indicator (LED)**

Recently EG&G ORTEC introduced the Gamma Gage, a field portable, "hand-held" high-purity germanium gamma-ray spectrometer with 8-hour liquid nitrogen holding time. Now, for those customers requiring longer holding time, we are offering a 24-hour Gamma Gage. Both are designed for applications requiring high-resolution spectroscopy at the source of the radiation and are ideal for routine inspections and emergency situations. Capable of driving up to 500-feet of cable, they allow you to take the spectrometer to the source of the radiation rather than taking samples to either an on-site or off-site laboratory.

The Gamma Gage is compact and lightweight (length <19 in., weight <8 pounds for 8-hour holding time and length <20 in., weight <11 pounds for 24-hour holding time). It comes in the exclusive EG&G ORTEC streamline cryostat configuration. These "all-attitude" Gamma Gages may be used when pointed at any angle, and are designed for use with GEM (HPGe coaxial), GMX (GAMMA-X coaxial), and SLP and GLP (LEPS) detectors.

Also featured is automatic high-voltage shutoff protection: if the LN_2 supply is exhausted and the detector starts to warm while bias is applied, these "smart" Gamma Gages will automatically turn off the high voltage from EG&G ORTEC's Model 459 Power Supply, thus protecting the FET from damage.

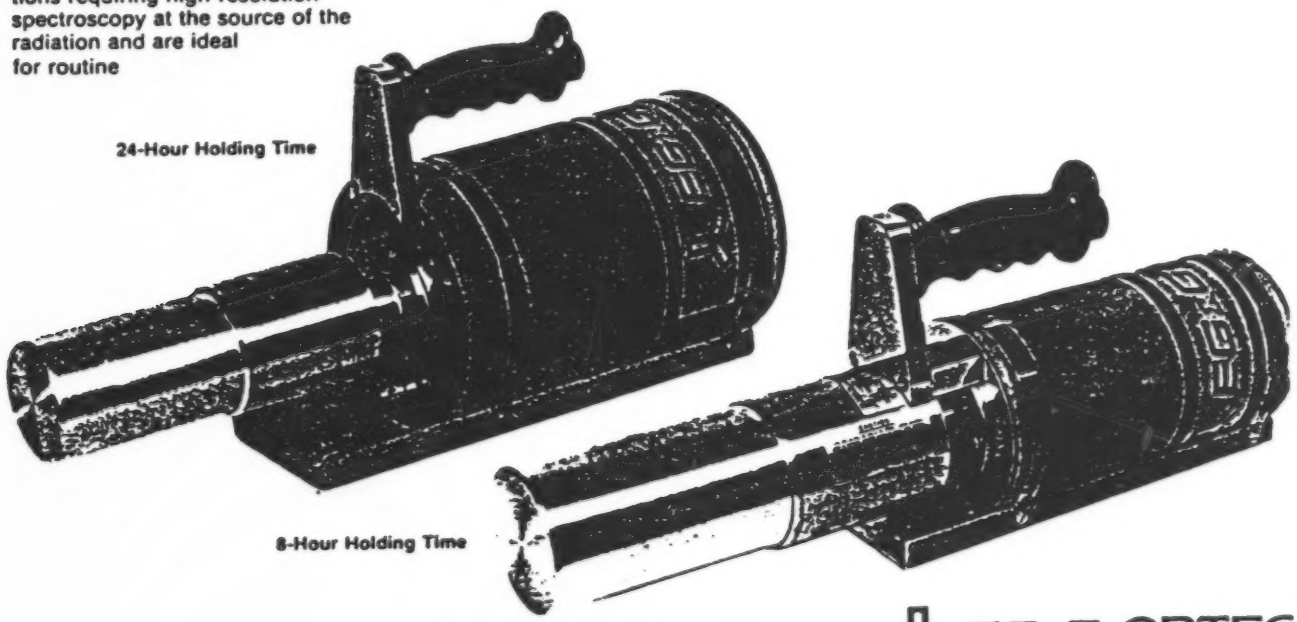
A high-count rate indicator, (LED), informs the user that excessively high-count rate has driven the preamplifier to a point where data is invalid.

When not in use, the Gamma Gage may be either stored at room temperature or attached to a 25-liter storage/fill dewar (available as an accessory). This storage/fill dewar keeps the Gamma Gage continuously filled with LN_2, insuring that it is always ready for use.

Since the carrying handle is easily removed, the Gamma Gage is also ideally suited for use in applications (such as reactor coolant pipe monitoring) where space is critically limited.

The standard all-attitude Gamma Gage includes the detector, preamplifier, high-voltage filter, handle, dewar, and manual LN_2 fill funnel. (An optional manually-operated fill system, with self-pressurizing dewar, is also available.)

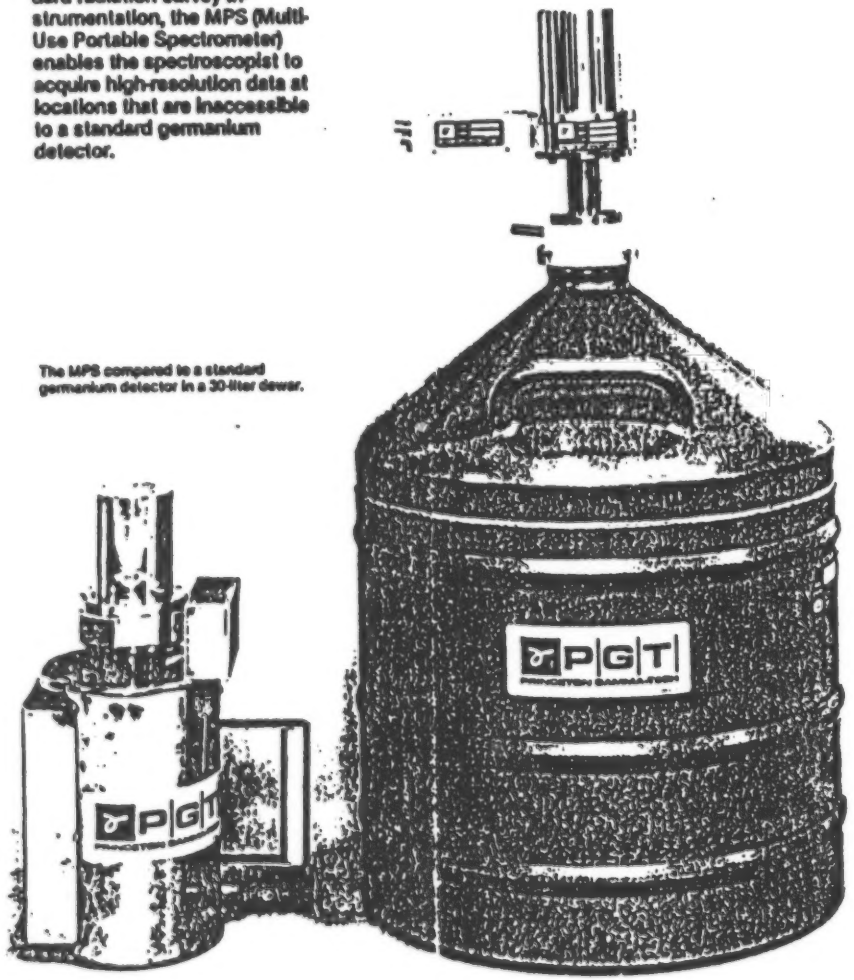
To order the detector with the particular specifications you desire, refer to the EG&G ORTEC Selection Guide and Price List. For the 8-hour holding time Gamma Gage, specify dewar DWR-0.4G; for the 24-hour holding time Gamma Gage, specify dewar DWR-1.2G.



Gamma Gage Portable Spectrometers

EG&G ORTEC

PGT's advanced germanium technology now permits total portability of a germanium spectrometer for in-situ analysis. Similar in use to standard radiation survey instrumentation, the MPS (Multi-Use Portable Spectrometer) enables the spectroscopist to acquire high-resolution data at locations that are inaccessible to a standard germanium detector.



The MPS compared to a standard germanium detector in a 30-liter dewar.

PGT's new Multi-Use Portable Spectrometer (MPS) offers today's nuclear industry a high-resolution portable germanium spectrometer for in-situ gamma or X-ray analysis.

The MPS is designed for use with any standard PGT Intrinsic Germanium detector. PGT's I G planar detectors are available up to 20 cm^2 active area and can be utilized in the energy range of 3 keV to 1.5 MeV, depending on their thickness. For applications in the energy range of 30 keV to 10 MeV, PGT offers I G coaxial detectors with efficiencies up to 35 percent and resolution performance to 1.7 keV (FWHM) at Co-60.

Because it employs a PGT Intrinsic Germanium detector, the MPS can be cycled to room temperature repeatedly or stored at room temperature indefinitely with no deterioration in performance.

Its spillproof design, rugged construction, and compact dimensions make the MPS a truly portable instrument. It can be pointed in any direction without LN spillage or placed upright and operated in a stationary position. Constructed of durable stainless steel, the 1.4 liter liquid nitrogen reservoir permits a minimum of 16 hours working time prior to refilling. The instrument is less than 16 inches in overall length and weighs 12 pounds when filled with liquid nitrogen.

The MPS includes a high-performance preamplifier supplied by PGT When used with PGT's spectroscopy amplifier and bias supply (or equivalent), the MPS is compatible with all presently available multichannel analyzers and data acquisition systems.